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COMPARISON OF MEASURED AND CALCULATED SOUND PRESSURE LEVELS AROUND A LARGE HORIZONTAL AXIS WIND TURBINE GENERATOR

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INTRODUCTION

There is a concern for the possible adverse environmental impact on nearby residents of the radiated noise from large wind turbines used for commercial power generation. There is thus a need for a systematically structured data bank to characterize the noise from such machines, as well as a need for validated methods of predicting noise for a range of conditions. A number of studies (Refs. 1-10) form the basis of existing knowledge of the noise characteristics of large horizontal axis wind turbines. Sound pressure level and spectral data are available for ranges of operating conditions for downwind configurations such as the WTS-4 (Refs. 1 and 2), the MOD-1 (Refs. 2, 3 and 10), the MOD-OA (Refs. 2, 5, 6 and 7), the US Windpower machine (Ref. 8) and the Maglarp machine (Ref. 9); and for upwind configurations such as the MOD-2 (Refs. 2 and 4) and the Nasudden machine (Ref. 9). These studies present measured data at various azimuth angles, typically upwind, downwind and crosswind, and contain valuable information about the generation and propagation of noise from large wind turbines. However, systemmatic data to precisely define the characteristics of the noise source are lacking. In particular, none of the previous studies have included simultaneous measurements at closely-spaced azimuthal locations.

The purpose of the present study is to provide detailed information on the noise generated by the WTS-4 wind turbine under various operating conditions. Data are presented for closely-spaced azimuthal measurement locations. This study represents a substantial extension to the experimental data base for the WTS-4 presented in Reference 1, and , in addition, presents comparisons between measurements and predictions for both the discrete frequency rotational harmonics and broadband noise components.

This effort is part of the Department of Energy Wind Energy Program which is managed by the Solar Energy Research Institute. The WTS-4 machine, the object of the present measurement program, was manufactured by the Hamilton Standard Division of United Technologies and was operated by the Department of the Interior, Bureau of Reclamation.

APPARATUS AND METHODS

Description of Site

Measurements were made at the operations site of the WTS-4 machine near Medicine Bow, Wyoming. The site is located in gently rolling open range territory that has an elevation of about 2075 m (6800 ft.) above sea level and is remote from airports and main highways. There are no trees and only sparse surface vegetation.

Wind velocity and direction were monitored and recorded continuously from meteorological instruments located at an elevation of 80 m and at a distance of about 300 m west (upwind) of the machine. For all data reported herein the wind direction varied from 250^{o} to 345^{o}, the wind velocity ranged from 7.11 m/s to 16.3 m/s (16 to 37 mph), the relative humidity varied from 22% to 41%, the barometric pressure varied from 777 mB to 800 mB, and the ambient temperature varied from 7^{o} to 18^{o}C. All data were recorded on June 10, 1985 between 0900 and 2200 hours; and on June 11, 1985 between 1500 and 1700 hours.

Description of Wind Turbine Generator

The WTS-4 wind turbine generator has a two bladed, 79.2 m (256.6 ft.) diameter, rotor mounted on an 80 m (263 ft.) high tower (see insert of figure 1) with a twelve sided cross section. The distance across the tower, between flats is 3.66 m (12 ft.). It is a downwind machine (inflow encounters the tower first before encountering the rotor) having a rated power output (P) of 4.2 MW. Its operational range of wind velocities (V) is about 7.1 m/s (cut-in) to (cut-out) 27 m/s (15.9 to 60.4 mph). The blades are pitch controlled at the root by a hydraulic control system and rotational speed is maintained at 30 rpm. Blades are tapered in chord from 1.04 m (3.4 ft.) at the tip section (NACA 23012 airfoil) to 4.75 m (15.6 ft.) at the root section (NACA 23036 airfoil). The twist angle varies from approximately -1^{o} at the tip to 16^{o} near the root.

In addition to normal machine operations at a range of wind speeds, special provisions were made to operate the machine at a rotational speed of 18 rpm, at skew angles of 20^{o} and 31^{o} with reference to the wind and for the conditions where the machine was disconnected from the power grid (zero output power).

ACOUSTIC MEASUREMENTS AND ANALYSES

The microphone locations are shown in figure 1. Eighteen fixed locations were chosen at 20^{o} intervals around the machine and at a distance of 200 m from its base. That distance was chosen to provide far field acoustic data with no significant atmospheric absorption effects.

All noise measurements and analyses were made with commercially available equipment. One-half inch diameter condenser microphones with a useable frequency range 3-20,000 Hz were used with two 14 channel FM tape recorders. The output signals of alternate microphones (9 channels) were recorded on each of two magnetic tapes for later analyses. All sound pressure level values in the paper are referenced to 2×10^{-5} pascals.

To minimize the detrimental effects of wind noise, standard polyurethane foam microphone wind screens were used and microphones were placed at ground level. Ambient noise data, obtained when the wind speed was 12.8 m/s and the wind turbine was rotating at 5 rpm, were used as a basis for signal to noise ratio estimation. In cases where one-third octave band data are shown without related ambient noise information it can be assumed that the signal to noise ratios were at least 3 dB.

In the frequency range 3-40 Hz, which contains many rotational noise components, narrow band ($\Delta f= .024$ Hz) analyses were performed. At the higher frequencies, characterized by broadband noise components, standard one-third octave band analyses were performed.

RESULTS AND DISCUSSION

Noise data presented herein were obtained from FM tape recordings and are given in the form of sound pressure time histories, narrow band spectra and one-third octave band spectra. Measured data are first presented to characterize the WTS-4 machine for normal operating conditions and then parametric variations are presented to illustrate the effects of wind speed, skew angle, rpm, time of day and on/off power grid connections.

Data for Basic Configuration

Sound Pressure Time Histories - Contained in figure 2 is an example sound pressure time history for the test machine. Note that there is a series of pulses superposed on broadband noise. The acoustic pulses, which occur at a 1 Hz repetition rate, correspond to the blade passages. Each time a blade passes through the tower wake a pulse is generated. The variations in acoustic pulse amplitude are believed to arise from corresponding variations in the transient aerodynamic loads on the blades as they traverse the tower wake. For the conditions of the tests the Reynolds number of the tower wake is estimated to be about 3×10^{6} and hence no strong periodicity would be expected (Ref. 3).

As each acoustic pulse is generated it propagates outward from the source in the manner suggested by the wave form photographs in figure 3. These wave forms were recorded from time synchronized magnetic tape records. All of the wave forms arise from the same pressure pulse which was recorded simultaneously at nine different microphones. It can be seen that the pulse amplitudes are highest in the upwind and downwind directions and are the lowest in the crosswind directions. Close inspection of the wave forms, as for example in figure 4, indicated that the upwind wave forms are the inverse (180^{o} out of phase) of those measured downwind, as might be expected from a source with dipole characteristics. This comparison is further demonstrated in figure 5 where the two traces of figure 4 are plotted together. Note that when one trace is inverted and slightly displaced in time the details of the two traces are seen to be remarkably alike.

Narrowband Analyses - The example narrow band ($\Delta f = .024$ Hz) harmonic levels of figure 6 illustrate the relative amplitudes of the rotational harmonics for upwind, downwind and crosswind measuring points, under normal machine operating conditions. Note that the symbols in figure 6 represent the levels of individual harmonics which are spaced 1 Hz apart in frequency. The connecting lines are added only for convenience in reading the figure. The spectral data represent two minute averages. Note that the spectra peak in the frequency range 4-8 Hz and the harmonic amplitudes decrease generally as frequency increases. The upwind and downwind spectra agree closely and are generally higher in level than the crosswind data. The exceptions are the data at 30 Hz. This 30 Hz component, which is believed to be a mechanical noise component associated with generator shaft speed, is observed only in the crosswind directions.

In order to characterize the directional properties of the machine as a low frequency acoustic radiator, the data of figure 7 are included. Shown are polar distributions of sound pressure levels for five different rotational harmonics. As indicated in figure 6, the upwind and downwind levels are about equal and in turn are higher than those measured in the crosswind direction.

Prediction of Discrete Frequency Components - Reference 11 contains a convenient method for predicting the rotational harmonic levels of wind turbines, provided the geometry and operating conditions of the rotor are known. It incorporates unsteady aerodynamic blade forces and is based on previous developments by Sears (Ref. 12) and Lowson (Ref. 13). Sample calculations for two different test conditions of the WTS-4 machine are presented in figures 8 and 9.

The data of figures 8 (a and b) relate to the narrow band spectra of the rotational harmonics for two different wind speed/power output condition. Figure 8(a) shows comparisons of calculated and measured noise levels for a high power condition of the machine. The general shape of the spectrum is predictable as are the levels of the strongest harmonics. Note that one of the inputs to the calculations is the velocity deficit in the tower wake since this is the main source of the fluctuating aerodynamic blade loads. The deficit is assumed to be a smooth function extending over an 8.5^{o} segment of the rotor disk (see sketch of Fig. 8). Based on unpublished manufacturers data, a deficit of 30% from mean flow values was assumed for most operating conditions but calculations for values of 20% and 40% are also shown in order to illustrate their sensitivity to changes in assumed velocity deficit. Figure 8(b) shows similar comparisons but for a low wind speed/power condition near cut-in. Note that the measured values are comparable in level to those for the higher wind speed in figure 8(a) and are substantially under predicted by the calculations. This latter discrepancy is not understood.

Comparisons of measured and calculated noise radiation patterns have been made for a number of harmonics and some examples are shown in figure 9(a) and (b) for the fourth (4 Hz) and the fifteenth (15 Hz) harmonics respectively. Calculated values in each case are a maximum on the axis (upwind and downwind) and a minimum in the plane of rotation. Measured values are in fairly good agreement with the calculations for angles near the axis of rotation but substantially exceed the calculations in the plane of rotation. This latter discrepancy is not understood but may arise because of effects of turbulence and blade thickness which are not accounted for in the calculations. The agreement shown in figure 9 is representative of that obtained for all intermediate harmonics. Higher harmonic (above 20 Hz) levels are generally underpredicted by the calculations.

Broadband Analyses - A one-third octave band spectrum for the same operating conditions as figures 6 and 7 is given in figure 10. The open data points were measured directly whereas the solid points were computed from the narrow band data of figure 6. The use of narrow band filtering in the presence of broadband ambient noise makes possible the definition of the individual rotational harmonic levels of figure 6 and their summations into one-third octave band levels in figure 10. Note that the spectrum peaks between 10 Hz and 20 Hz and falls off as frequency increases up to the limit of the analysis.

Sound pressure levels for four different one-third octave bands are shown in the broadband polar diagrams of figure 11. These latter data are for the same operating conditions as those of figures 6, 7 and 10. Note that the highest measured levels are in the upwind and downwind directions and the lowest levels are in the crosswind directions.

Predictions of Broadband Noise - A method is presented in Ref. 14 for predicting the broadband noise spectra of horizontal axis machines. It includes contributions from such sources as the inflow turbulence to the rotor, the interactions between the turbulent boundary layers on the blade surfaces with their trailing edges, and the wake due to the blunt trailing edges. The method is partly empirical, predicts levels only at frequencies above the 50 Hz one-third octave band and is based on data from airfoils and full scale wind turbines. Resulting calculations, as represented by the dashed curve of figure 10, are seen to be in good agreement with the measurements for an on-axis observation point.

Ambient Noise - Ambient noise, except for that generated by the wind, is generally low at this site because of the scarcity of road vehicles and aircraft, and only occasional trains. The ambient noise spectrum of figure 10 is mainly due to the effects of the wind. It peaks at low frequencies and drops off in level very rapidly with increased frequency. Thus ambient noise problems for these types of measurements are generally limited to the lower frequencies for which wind noise maybe dominant. This is further illustrated by the narrow band ambient noise spectrum of figure 6. Dynamic range characteristics of the tape recorder limit the high frequency measurements to about 2000 Hz and the low values of sound pressure level to about 45 dB.

Parametric Evaluations

During these tests there were provisions for evaluating the effects on the radiated noise of changes in the operating conditions of the machine. These results are presented in figures 12-20.

Effects of Wind Speed/Power Output - Figure 12 presents one-third octave band data obtained for wind speeds varying over a factor of two; the 15.2 m/s wind speed data being replotted from Refs. 1 and 14. At the lower frequencies, dominated by rotational harmonics, the highest levels are associated with the highest wind speeds. At the higher frequencies, dominated by broadband components, there is no clear trend of the data. Gaps in some broadband spectra in the frequency range 13-50 Hz are due to insufficient signal to noise ratio of the measured data.

Effects of On/Off Connections to the Power Grid - Data are presented in figure 13 to illustrate the effects on the measured noise of having the machine either connected to or disconnected from the power grid. Note that when disconnected from the grid the blade pitch angles are adjusted to maintain constant rotor speed. The net result is that the inboard sections are developing positive thrust while the outboard sections are developing negative thrust.

At moderate wind speeds, the noise spectra in figure 13 (a) are similar but with somewhat lower levels being associated with off-grid conditions. On the other hand there are notable differences at high wind speed as seen in figure 13 (b). Lower levels at the lower frequencies and higher levels at the higher frequencies result from the off-grid operating conditions. These latter results are probably due to the associated off design aerodynamic operating conditions of the blades.

Effects of Skew Angle - Wind turbines sometimes operate such that the inflow is not aligned with the thrust axis. This may occur either because of the natural variation of the wind or because the machine is skewed out of the wind to reduce the aerodynamic loads during extreme winds. In either case there is a concern for the effects of skewness on the radiated noise. A series of measurements was performed at skew angles of 20^{o} and 31^{o} and the results are compared with results for the unskewed condition (0^{o}) in figure 14. Data are included for four locations in each of the downwind and upwind quadrants. The arithmetic averages of the measured levels are represented by the three curves of figure 14. At the lower frequencies which are dominated by the rotational harmonics the sound pressure levels are reduced as the skew angle is increased. This result is expected since the skewed blades encounter the tower wake at a reduced angle and at an increased distance from the tower. The data of figure 14 suggest that the levels at the higher frequencies which are dominated by broadband noise, increase slightly as skew angle increases.

Effects of RPM - Special provisions were made to operate the machine at two different rotational speeds while disconnected from the power grid. The effects of reduced RPM on the measured one-third octave band spectra of the radiated noise, both upwind and downwind of the machine, are shown in figure 15. Also shown are calculated curves by the method of Ref. 14. Note the calculated curves for the upwind condition at 30 rpm. the dotted curve is based on the assumption that only 100 kW of power were produced to overcome the losses in the system. Agreement with measured data is better for the solid curve for which a power output approximating normal on-grid operation at the same wind conditions is assumed (1000 kW). The explanation for this apparent anomaly is that the prediction method of Ref. 14 assumes that the turbulence intensity is related to power rather than wind speed. Better agreement is obtained between measured and calculated values when normal values of power, consistent with the existing wind speed, are assumed. Such an assumption was made for all of the solid and dashed curves of figure 15. Fair agreement is indicated between measured and calculated values for both rotational speeds. Calculations indicate a 10-15 dB reduction of sound pressure level for a change in rpm from 30 to 18 rpm.

Effects of Time of Day - Observations and measurements at the test site indicated that the atmospheric conditions after dark were significantly different than those during daylight hours. In particular the turbulence levels of the inflow to the turbine were judged to be lower at night. The resulting differences in the radiated noise during the day and at night for comparable operating conditions are illustrated in figures 16-19.

Figure 16 presents narrow band harmonic levels up to about 40 Hz for upwind, crosswind left, crosswind right and downwind locations and for operations during the day and at night. In the upwind and downwind cases the levels are comparable but the crosswind levels are generally lower at night. This result of generally lower levels at night, particularly in the crosswind direction is illustrated also in figure 17 which presents polar diagrams for several different rotational harmonics.

The comparable broadband data for the same test conditions are included in figures 18 and 19. Figure 18 presents the on-axis data and it can be seen that the lower levels below about 300 Hz, are generally associated with night time operation. Similar results in polar diagram form are presented in figure 19 for four different one-third octave bands. Levels measured at night are generally lower, particularly at the crosswind locations.

CONCLUDING REMARKS

The radiated noise from the WTS-4 machine consists of a series of pressure pulses superposed on broadband noise components. The pressure pulses arise from tower-wake blade interactions and the broadband components are believed related to inflow turbulence ingestion, turbulent boundary layer - trailing edge interactions and blade trailing edge wakes.

Pressure pulses recorded at the upwind and downwind measurement locations exhibit a 180^{o} phase difference. In the frequency domain these pulses are represented by rotational harmonics, about 40 of which are identifiable from narrow band analyses for normal machine operations. The spectra peak at about 4-10 Hz and decrease in level with increasing frequency. The highest levels are measured upwind and downwind of the machine. Lower rotational harmonic levels are measured at night when the inflow turbulence is apparently less intense, at lower wind speeds and for conditions where the machine is skewed away from the wind vector.

The higher frequency noise is broadband in nature, peaks at frequencies below 50 Hz and the band levels decrease with increasing frequency. During the night the lower frequency one-third octave band levels are somewhat reduced relative to the daytime levels. Reduced rotational speed results in lower levels for all frequency bands. The broadband noise levels are relatively insensitive to wind speed, skewness with respect to the wind vector and to connection with the power grid.

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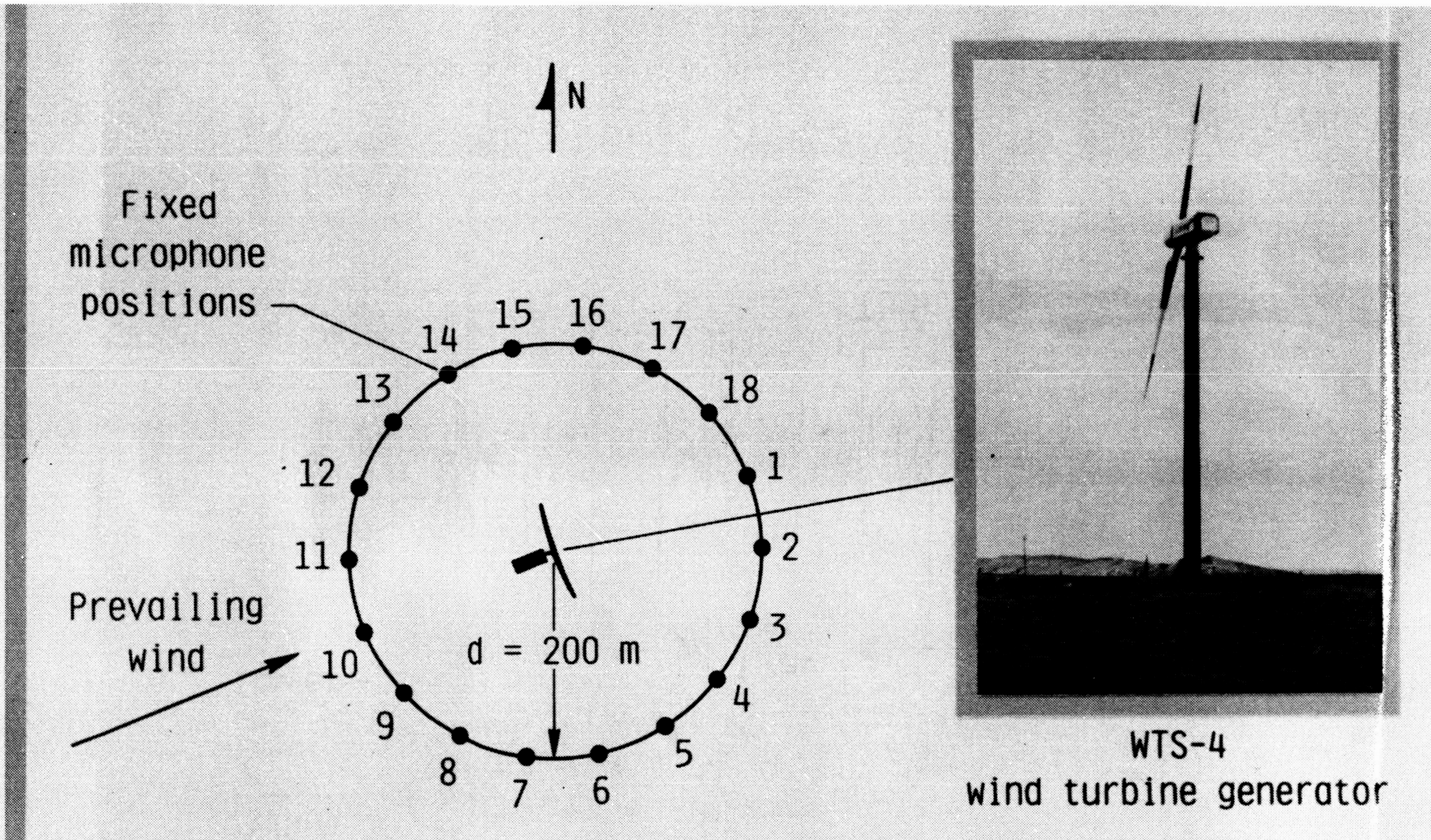

FIGURE 1. Microphone Locations for Circular Array Tests.

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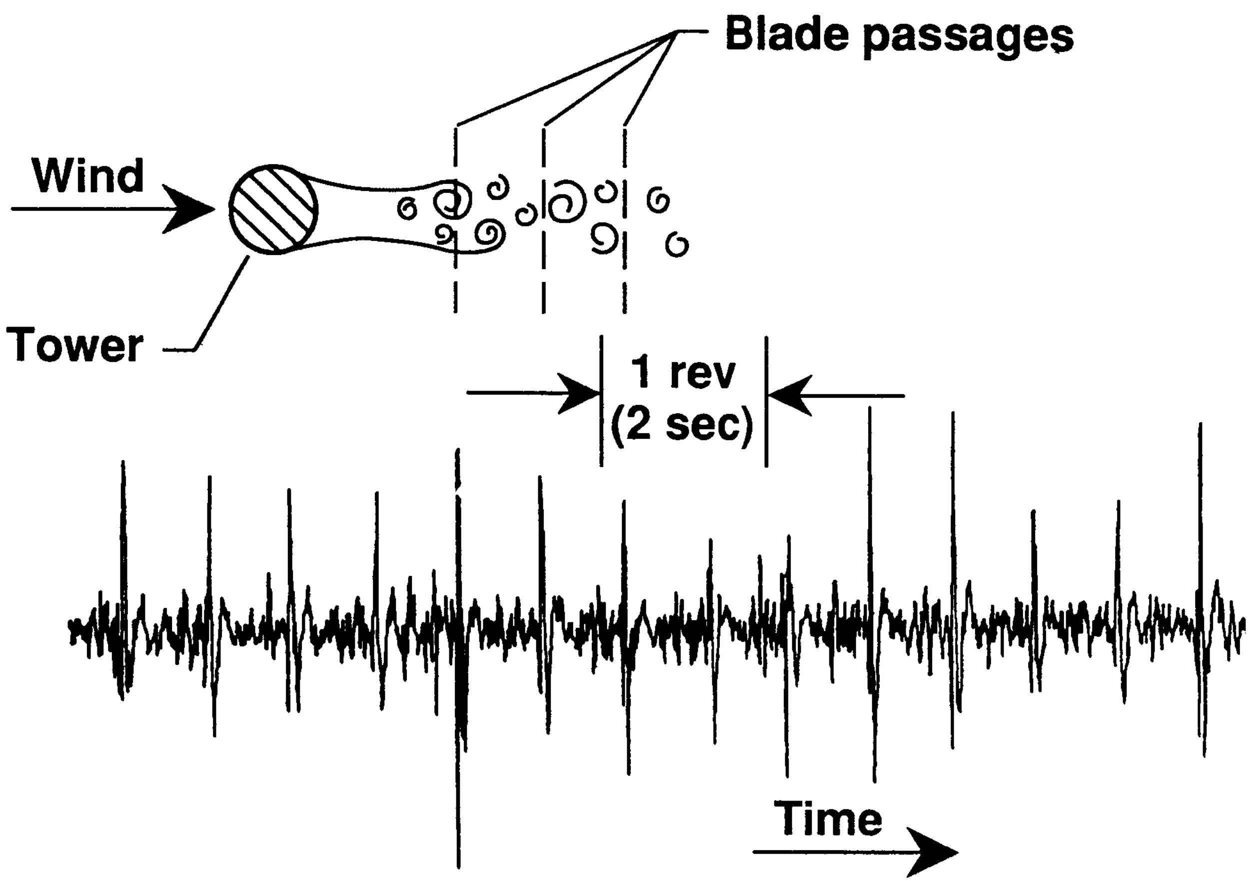


Figure 2 - Example sound pressure time history.

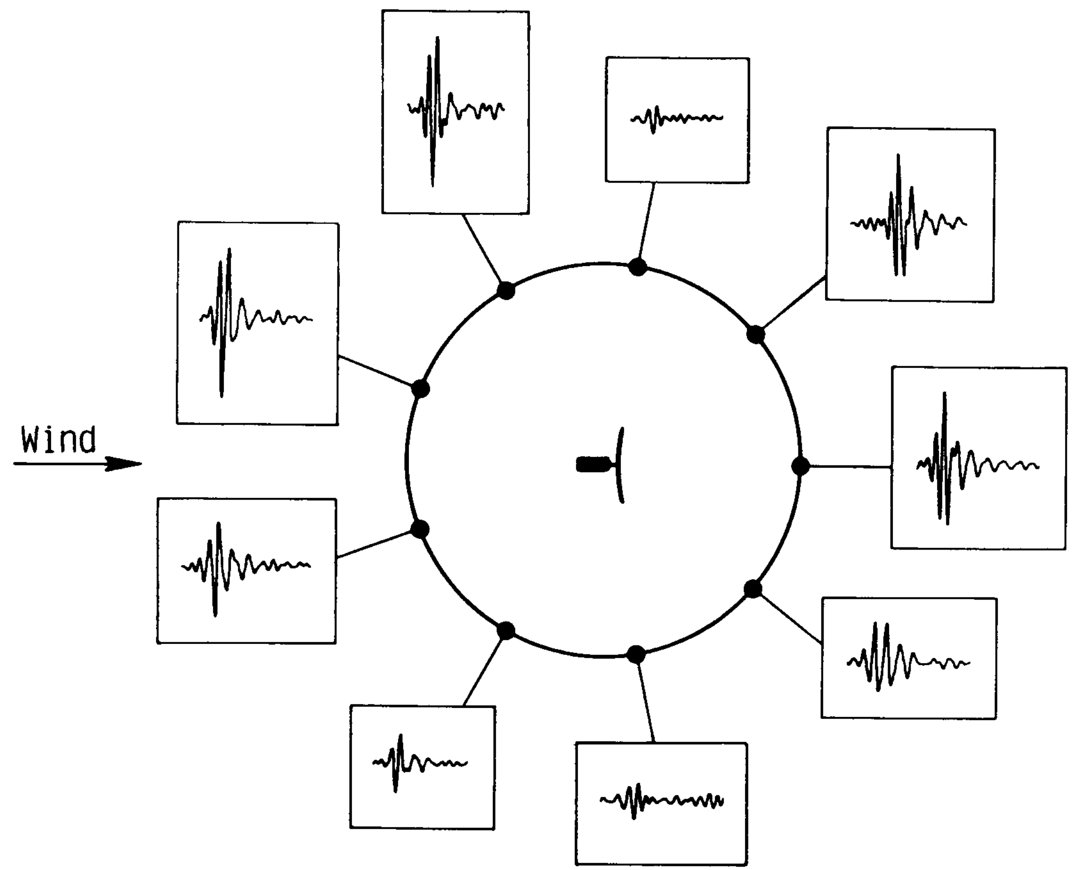


FIGURE 3.- Simultaneous Sound Pressure Pulses recorded during Normal Operations of the WTS-4 Machine at Nine different Equidistant Locations.

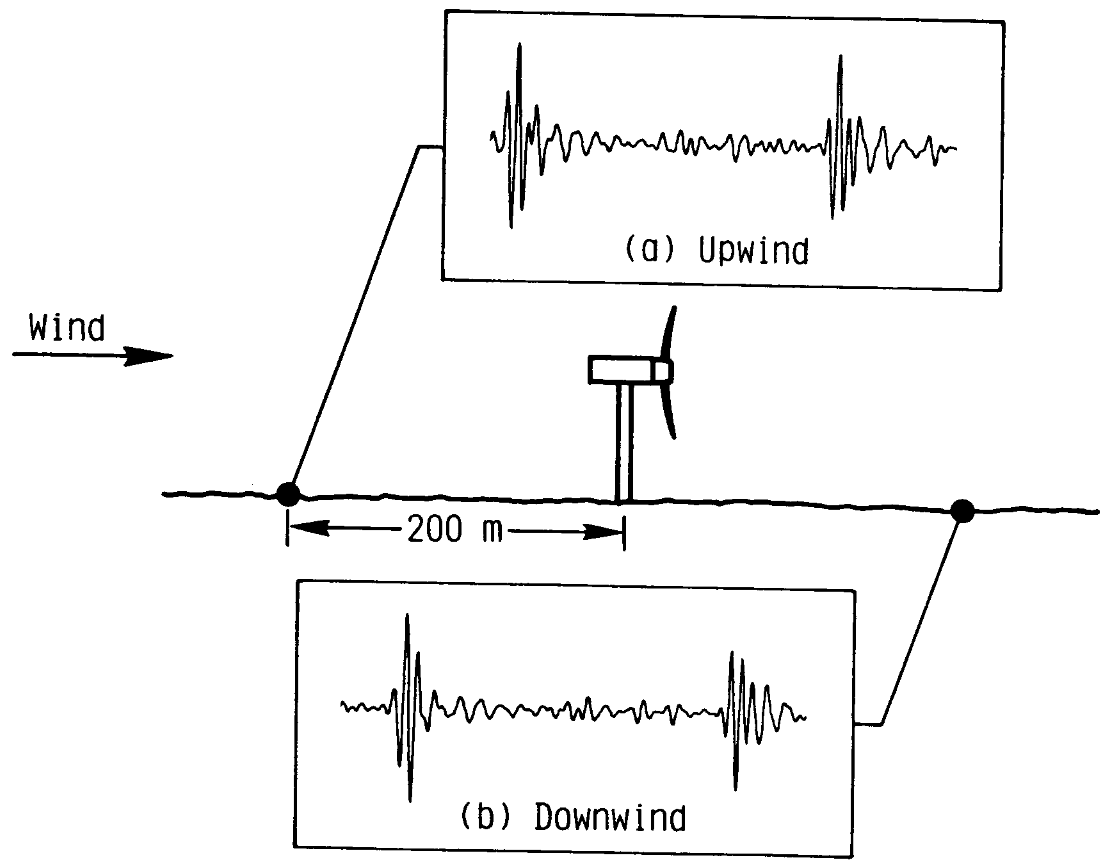


FIGURE 4.— Comparison of Sound Pressure Wave Forms Measured Simultaneously Upwind and Downwind of the WTS-4 Machine during Normal Operations.

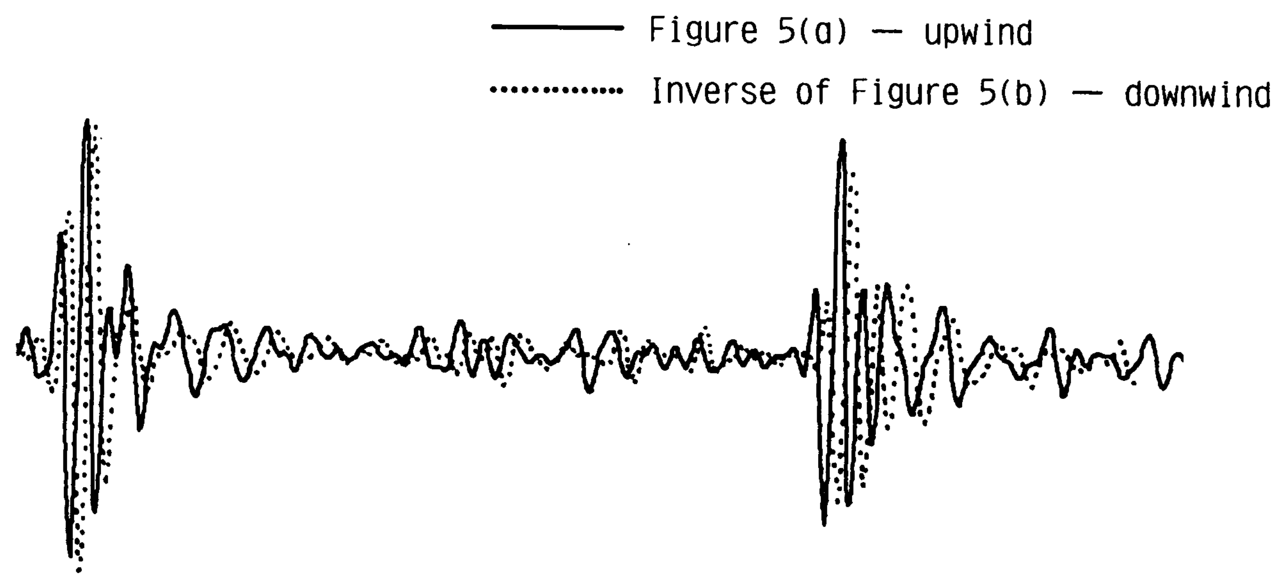


FIGURE 5.— Comparison of Sound Pressure Wave Forms Measured simultaneously Upwind and Downwind. The dotted Trace Corresponds to that of Figure 4(b) Inverted and Displaced slightly in time.

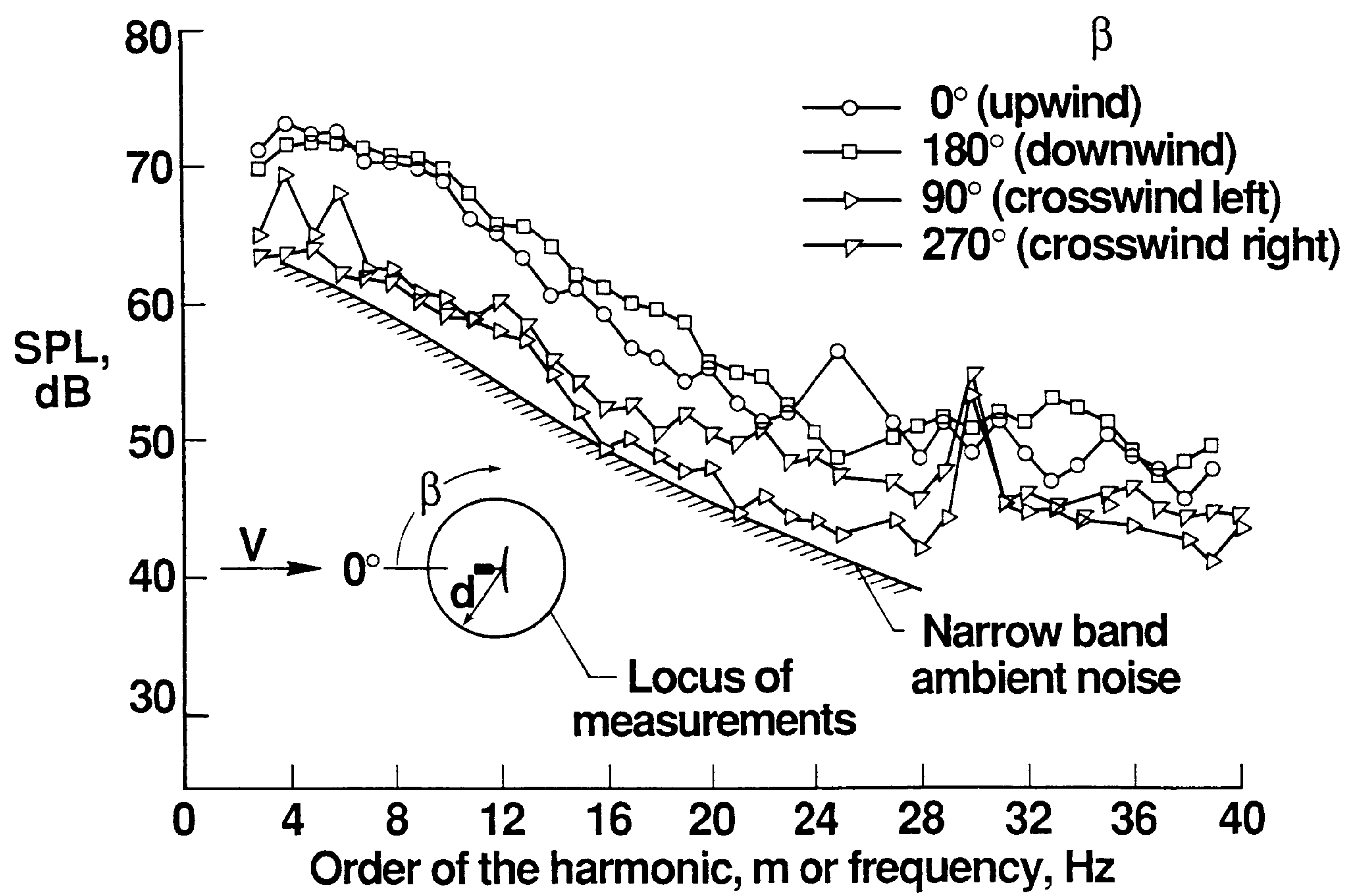


FIGURE 6.— Narrow Band (Δf= .024Hz) Spectra for Various Directions from the WTS-4 Machine. V=12.1 m/s, P=2.05 MW, d= 200 m, RPM=30.

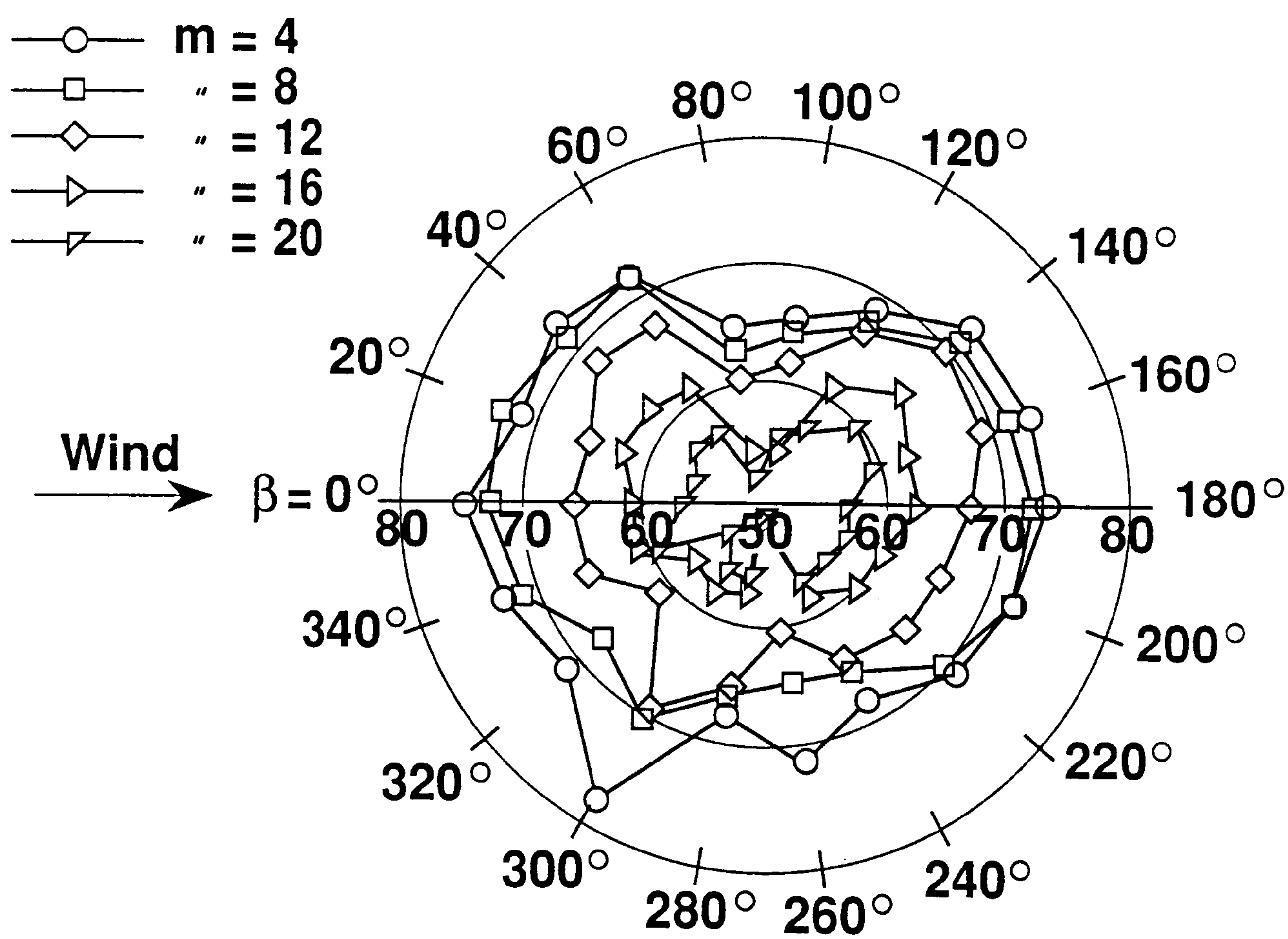


FIGURE 7.— Polar Distribution of Sound Pressure Levels for Various Rotational Harmonics Generated by the WTS-4 Wind Turbine Generator. V=12.1 m/s, P=2.05 MW, d= 200 m, RPM=30.

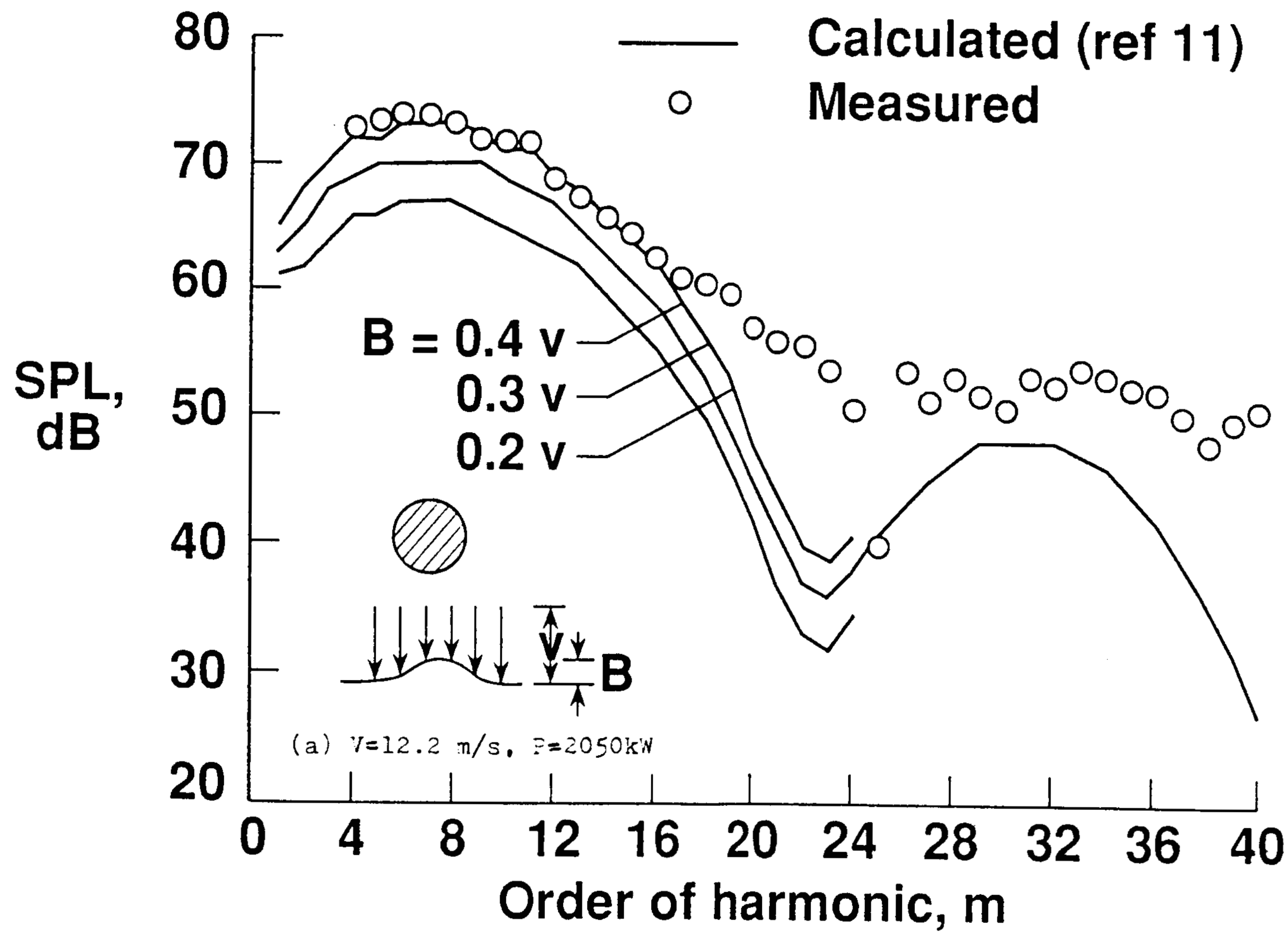


Figure 8.- Comparisons of measured and calculated on-axis spectra for the WTS-4 machine at two wind speeds. d=200m, RPM=30.

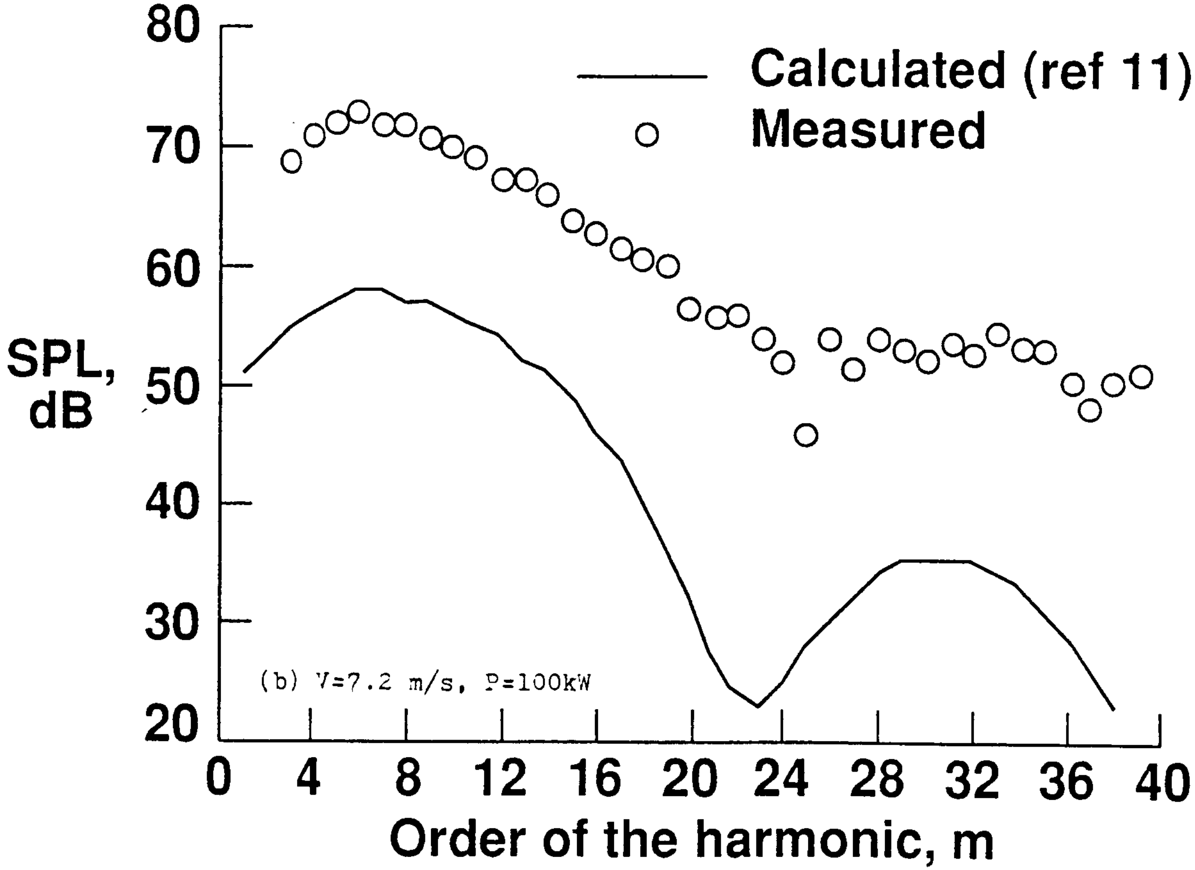


Figure 8.— (CONCL.)

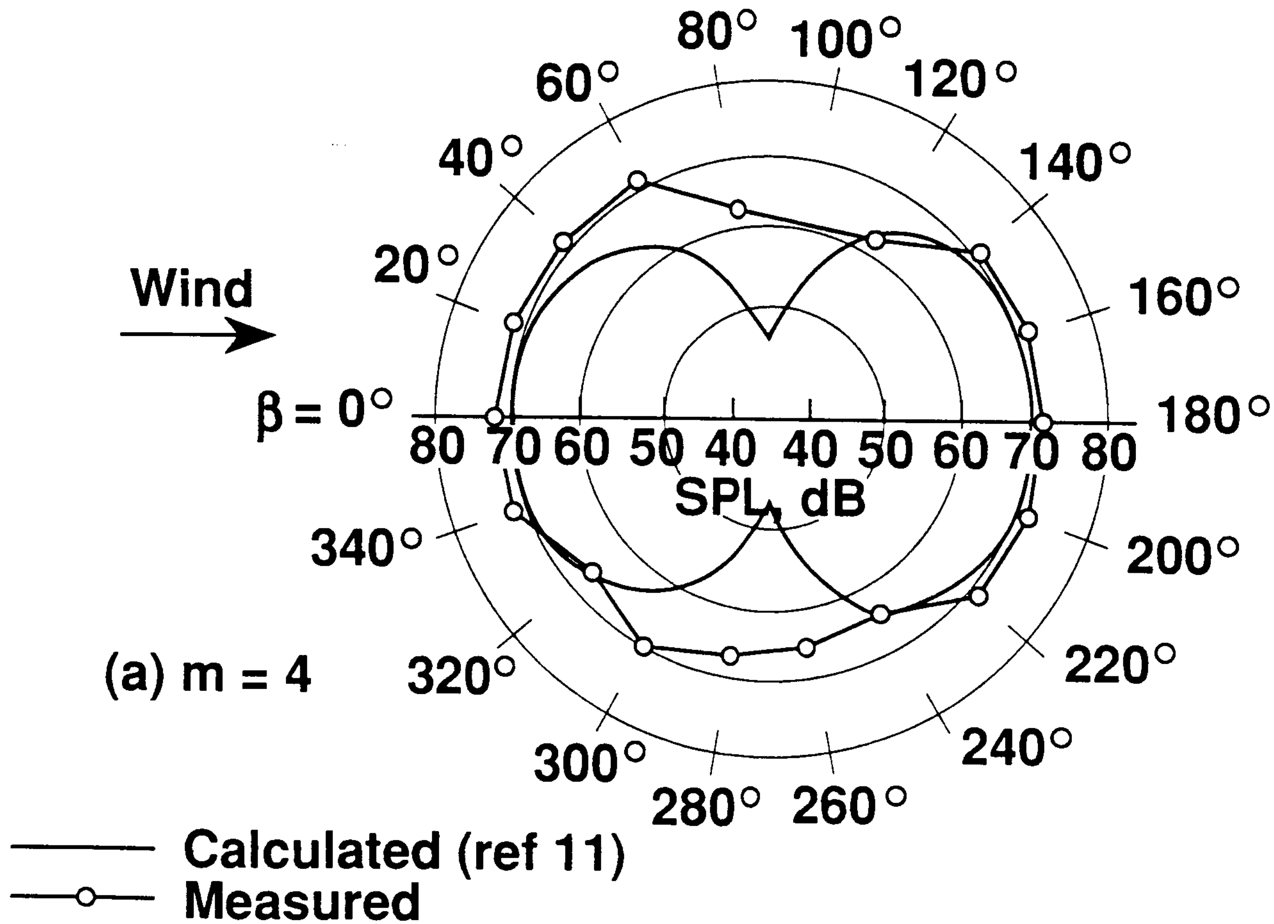


Figure 9.- Comparisons of measured and calculated noise radiation patterns for two rotational harmonics of the WTS-4 machine. d=200m, V=12.2 m/s, P=2050kW, RPM=30.

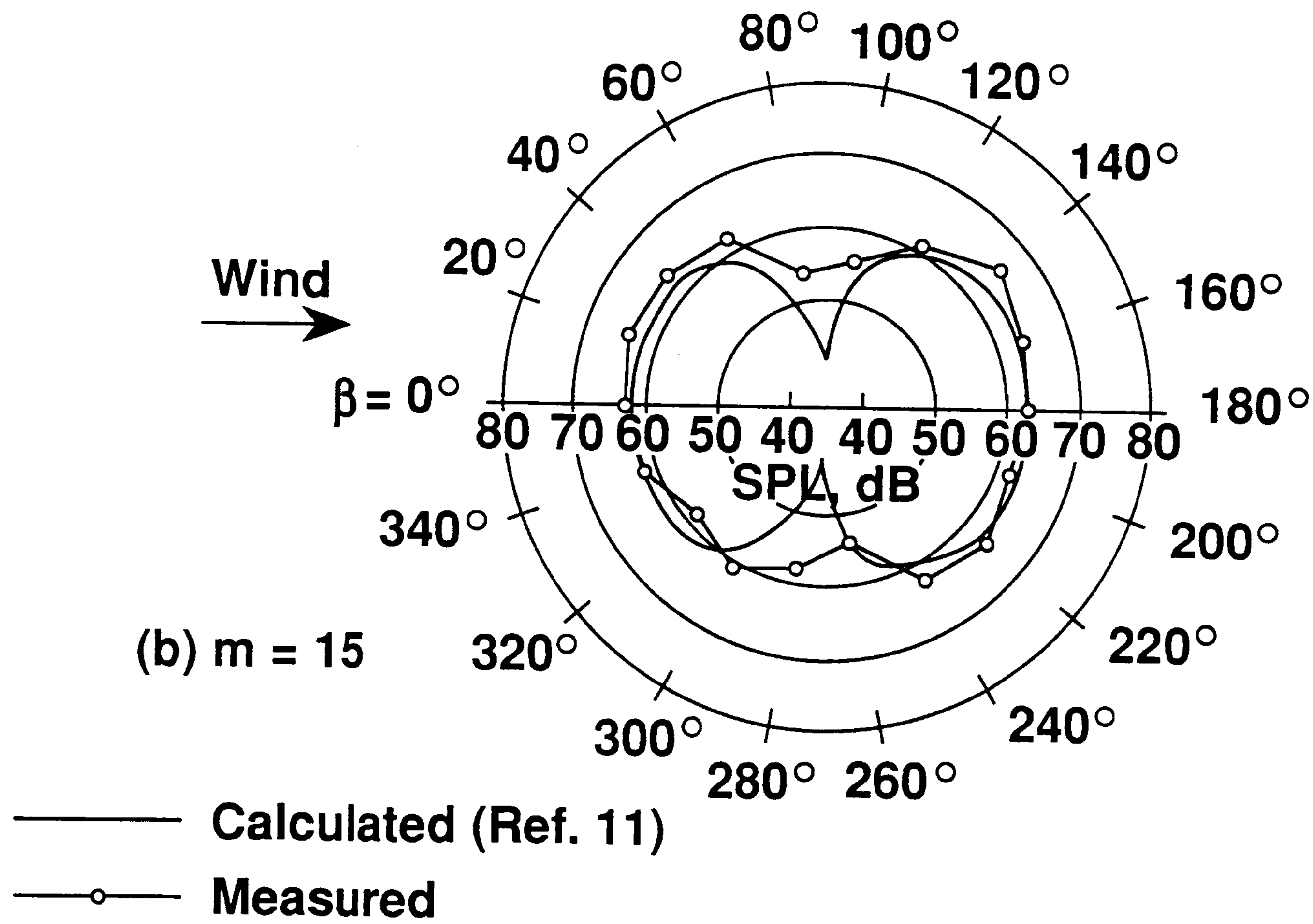


Figure 9. – (CONCL.)

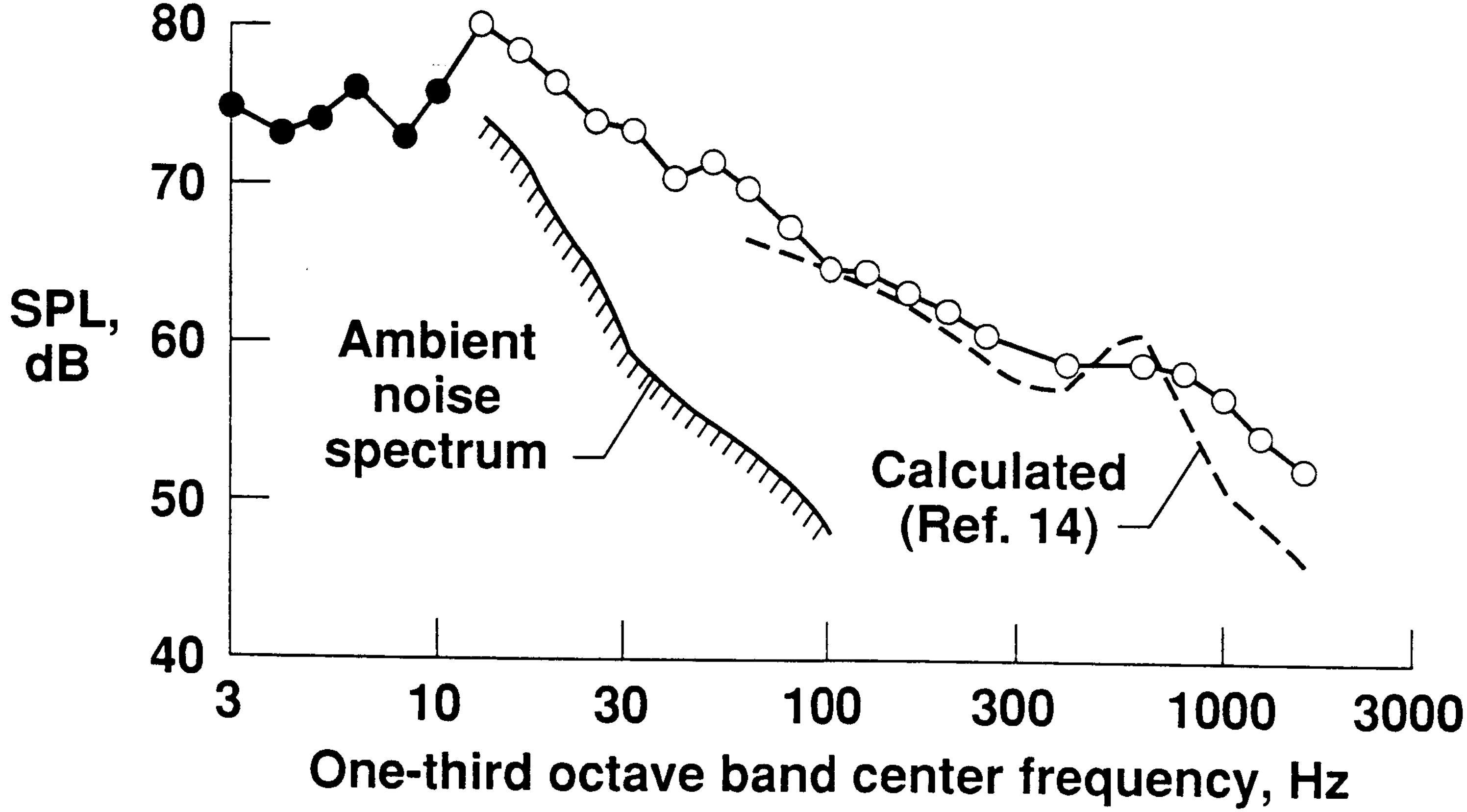


FIGURE 10.— One-Third Octave Band Spectrum of the Noise Downwind of the WTS-4 Wind Turbine Generator. V=12.1 m/s, P-2.05 MW, d=200 m, RPM=30.

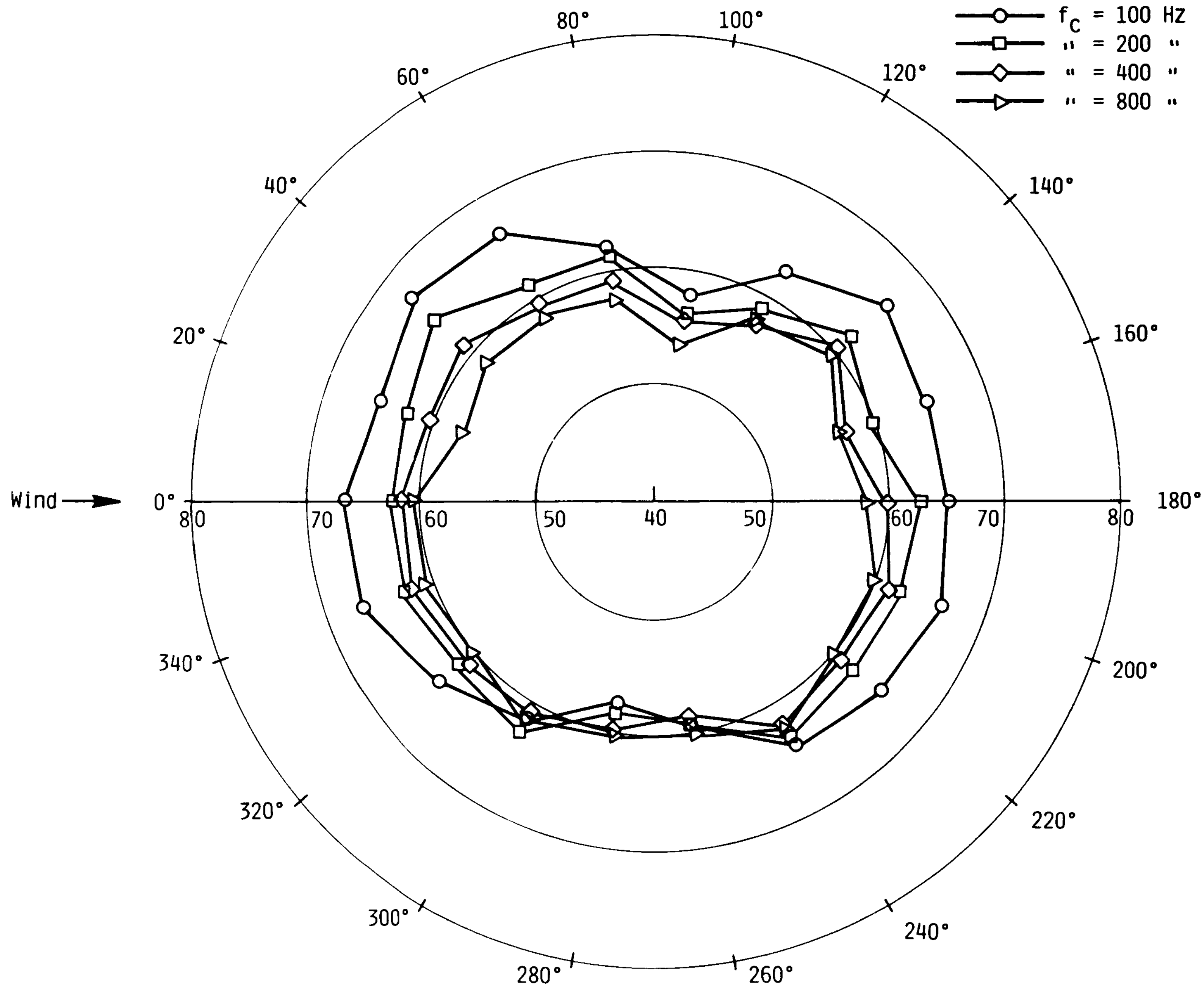


FIGURE 11. — Broad Band Polar Diagrams for the WTS-4 Wind Turbine Generator. V=12.1 m/s, P=2.05 MW, d=200 m, RPM=30.

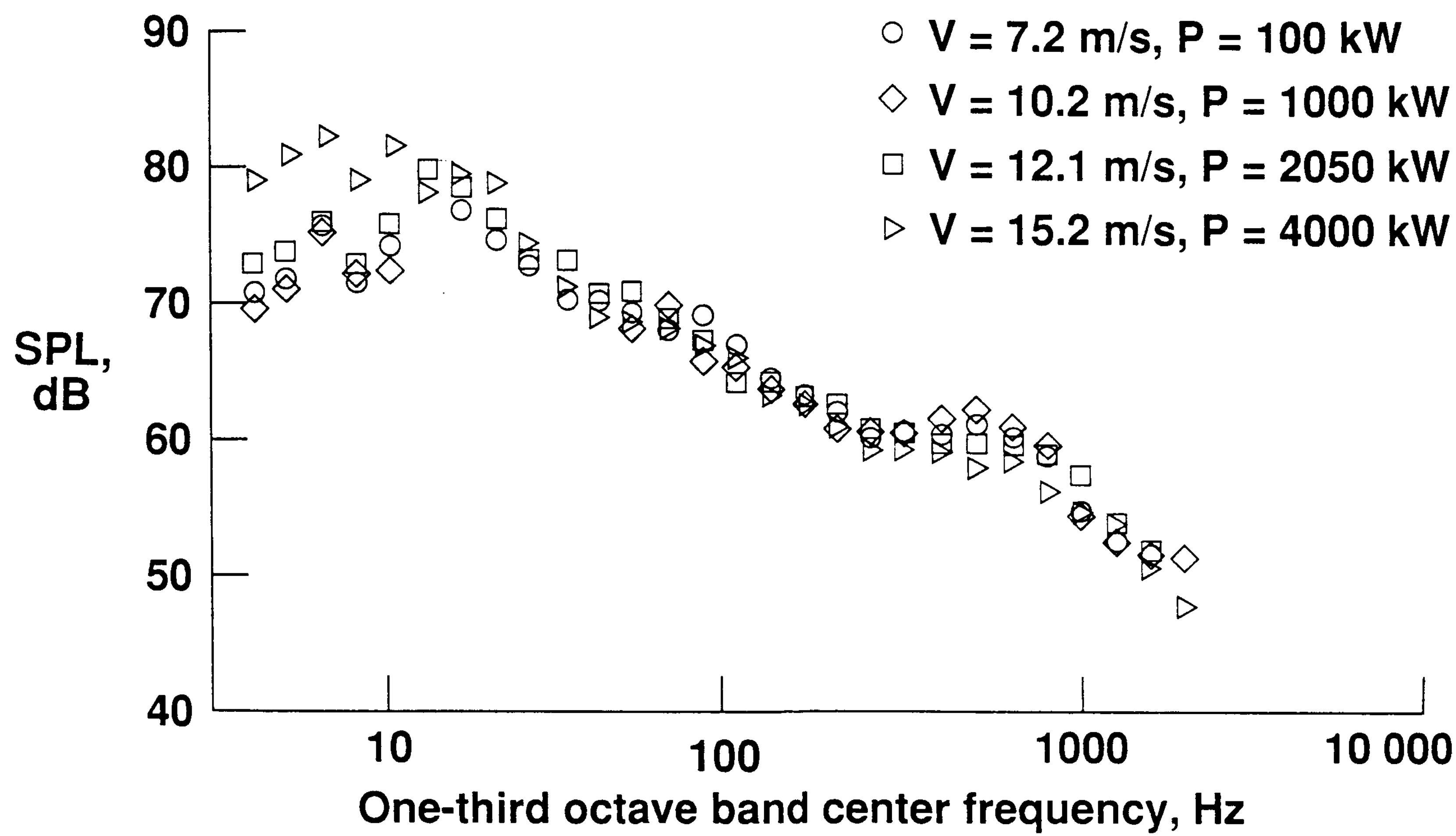


FIGURE 12. – Comparisons of One-Third Octave Band Spectra for Four Different Wind Speed/Power Outputs.

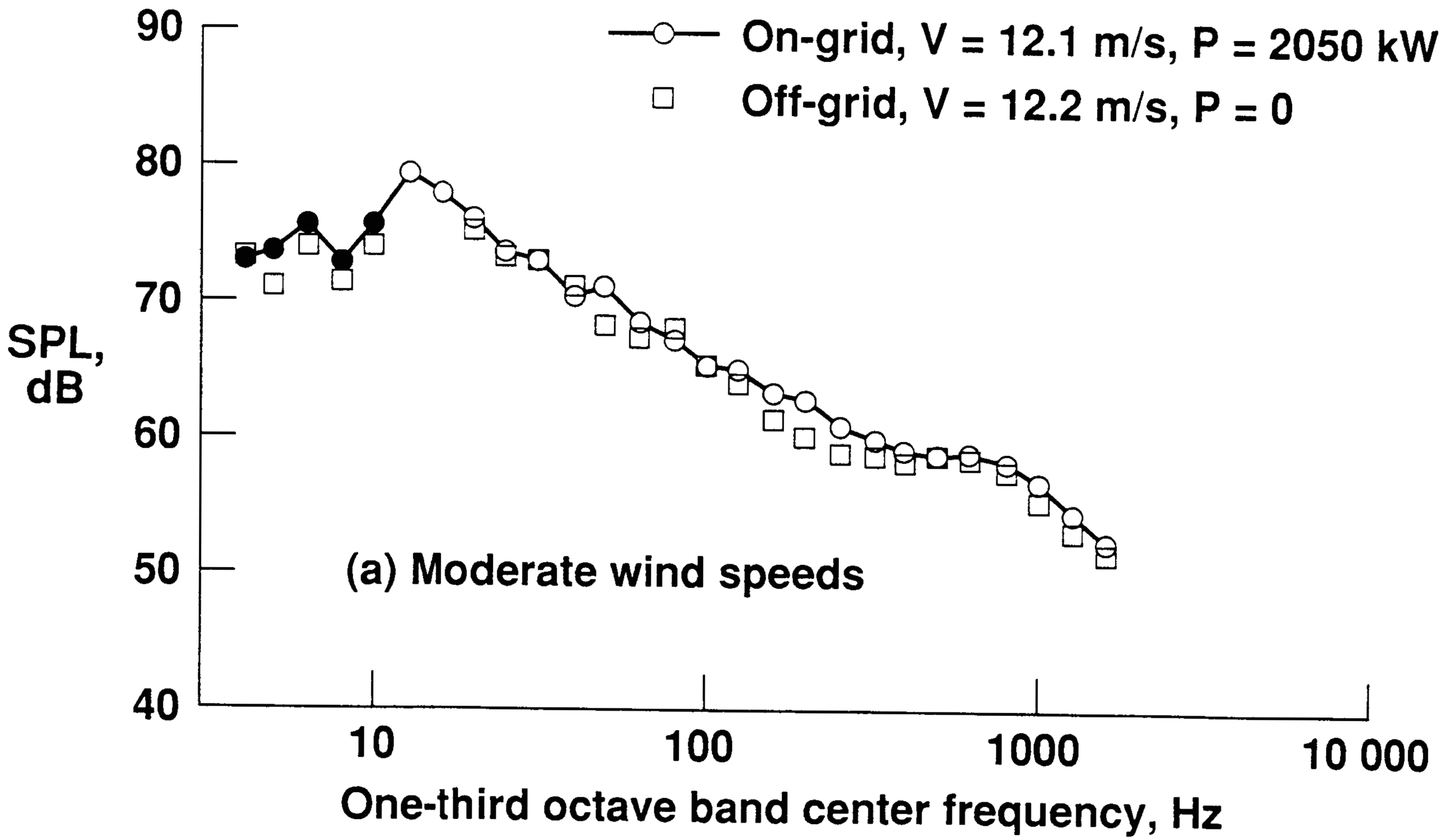


Figure 13 - Comparisons of one-third octave band noise spectra downwind from the WTS-4 machine both on and off the power grid at a distance of 200 m.

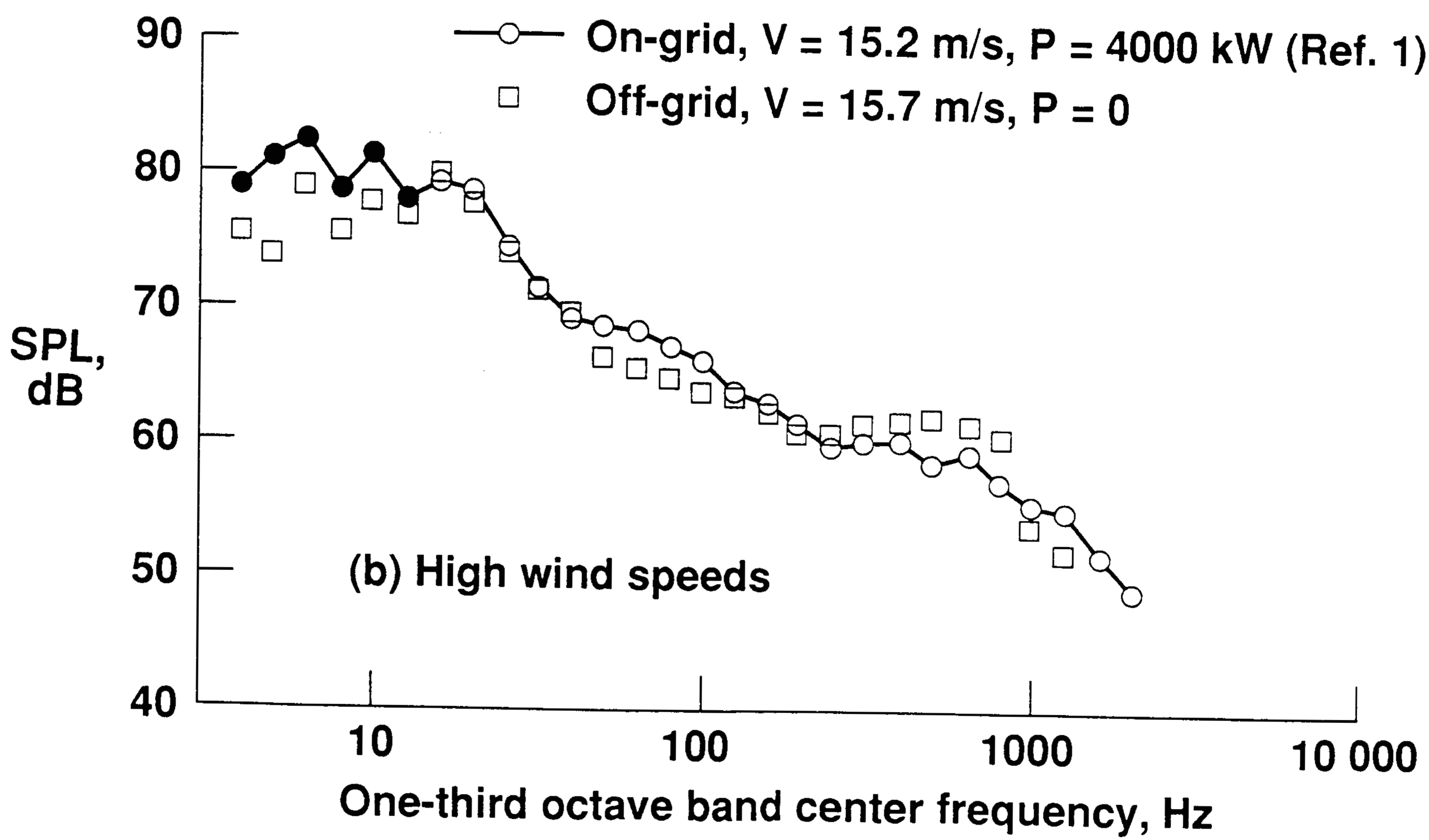


Figure 13 - (Concl.)

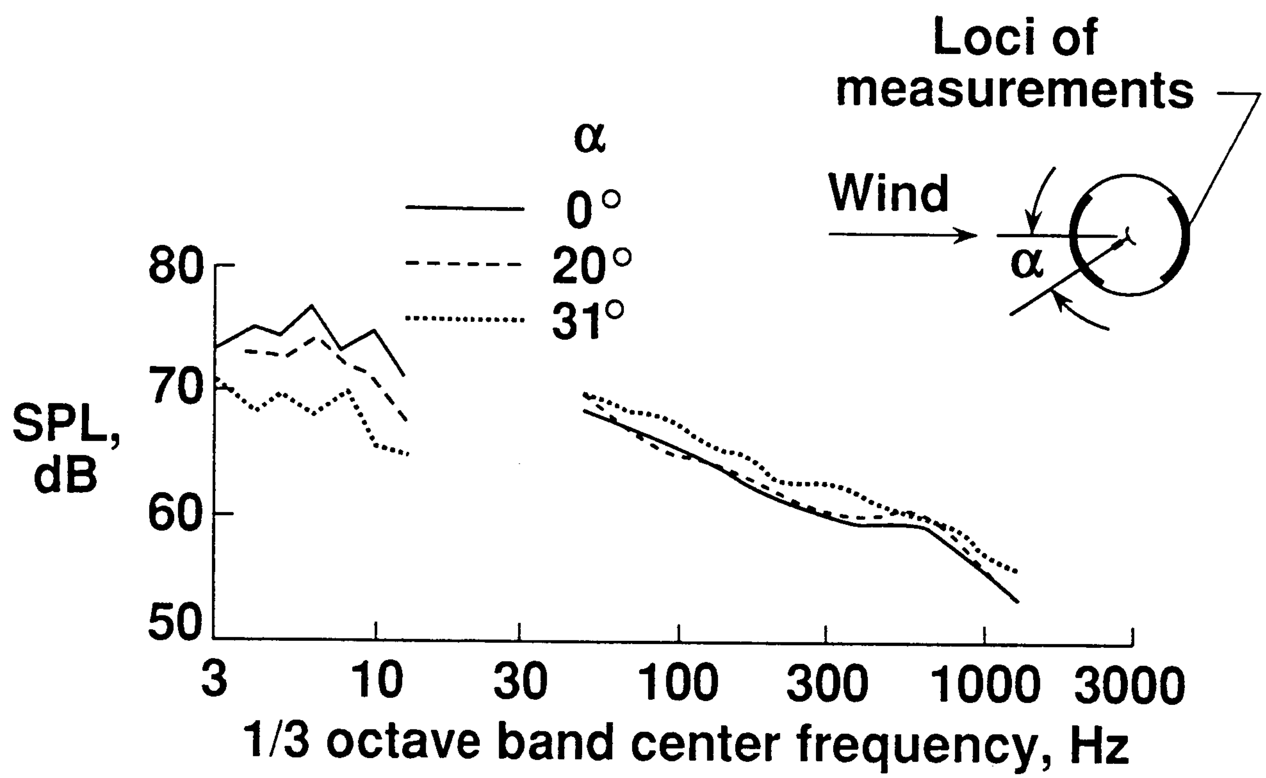


FIGURE 14.— Comparisons of One-Third Octave Band Spectra of the WTS-4 Wind Turbine Generator at Three Different Skew Angles with Reference to the Wind Vector.

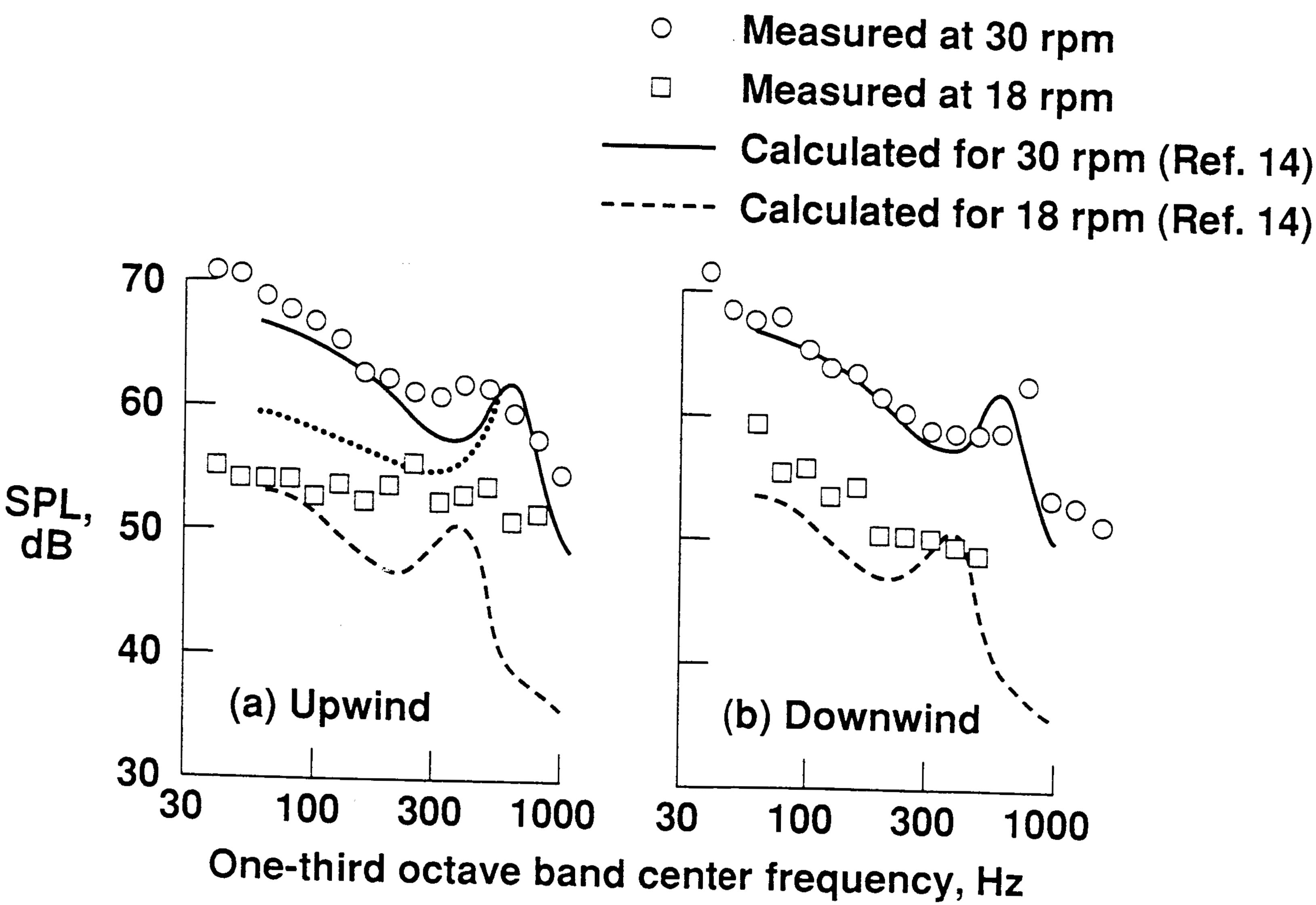


Figure 15 - Comparisons of measured and calculated one-third octave band noise spectra for the WTS-4 wind turbine generator at two rotational speeds during off-grid operation. d = 200 m, V = 11.0-12.2 m/s.

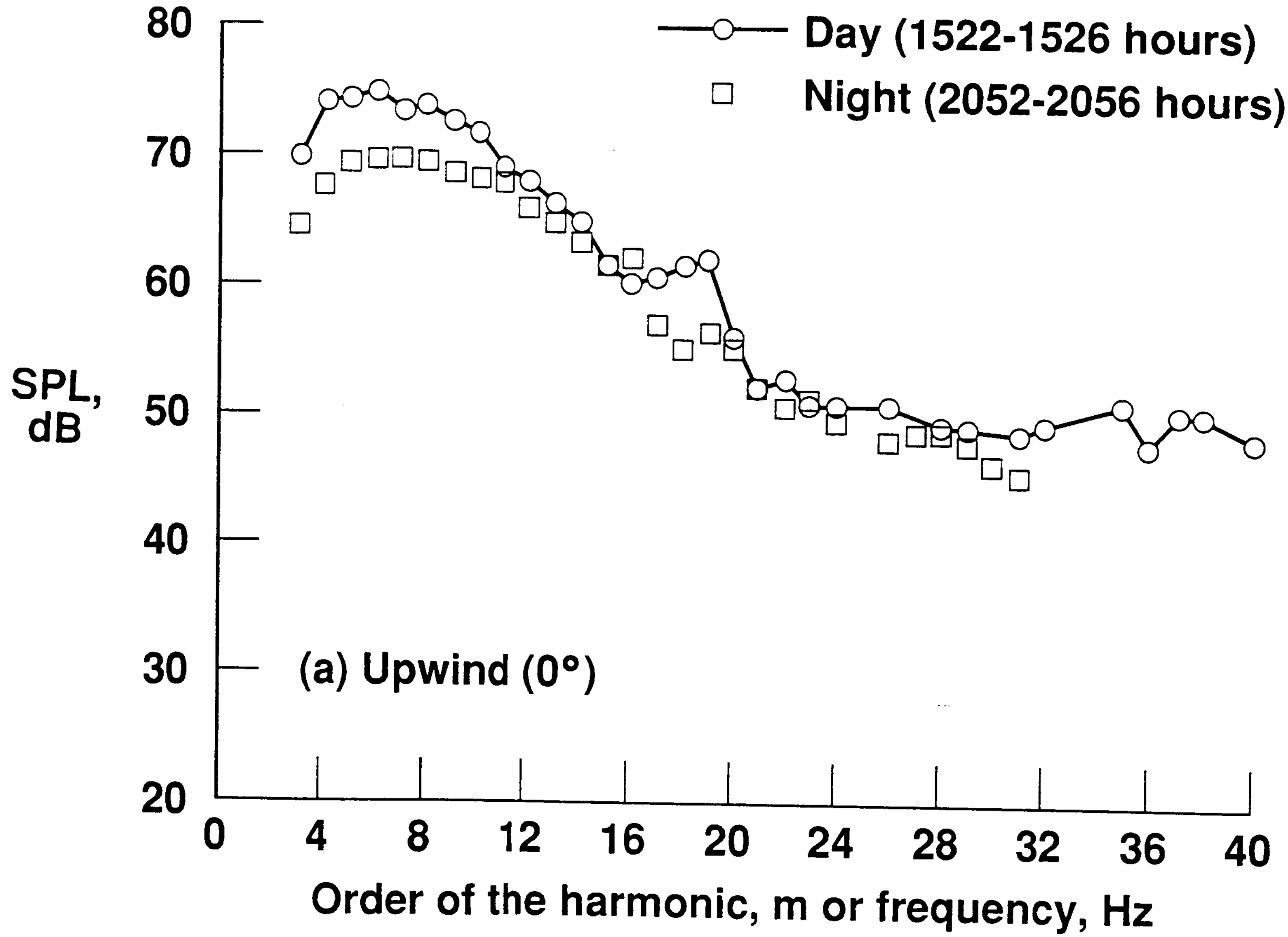


FIGURE 16. - Effects of Time of Day on the Narrow Band (Δf=.024Hz) Noise Spectra of the WTS-4 Wind Turbine Generator. V=7.2-7.4 m/s, P=0.10-0.13 MW, d=200 m, RPM=30.

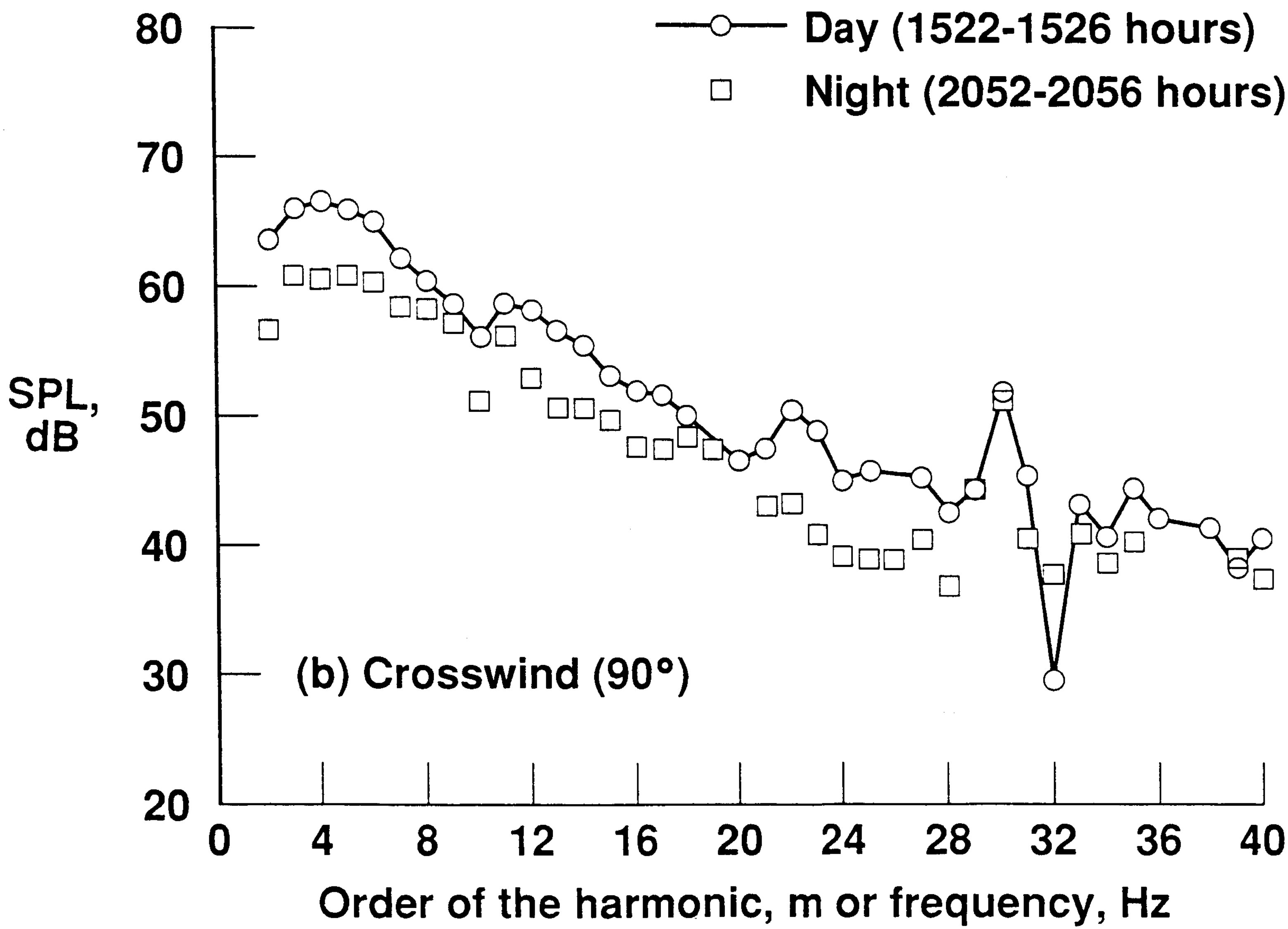


FIGURE 16. - (CONT.)

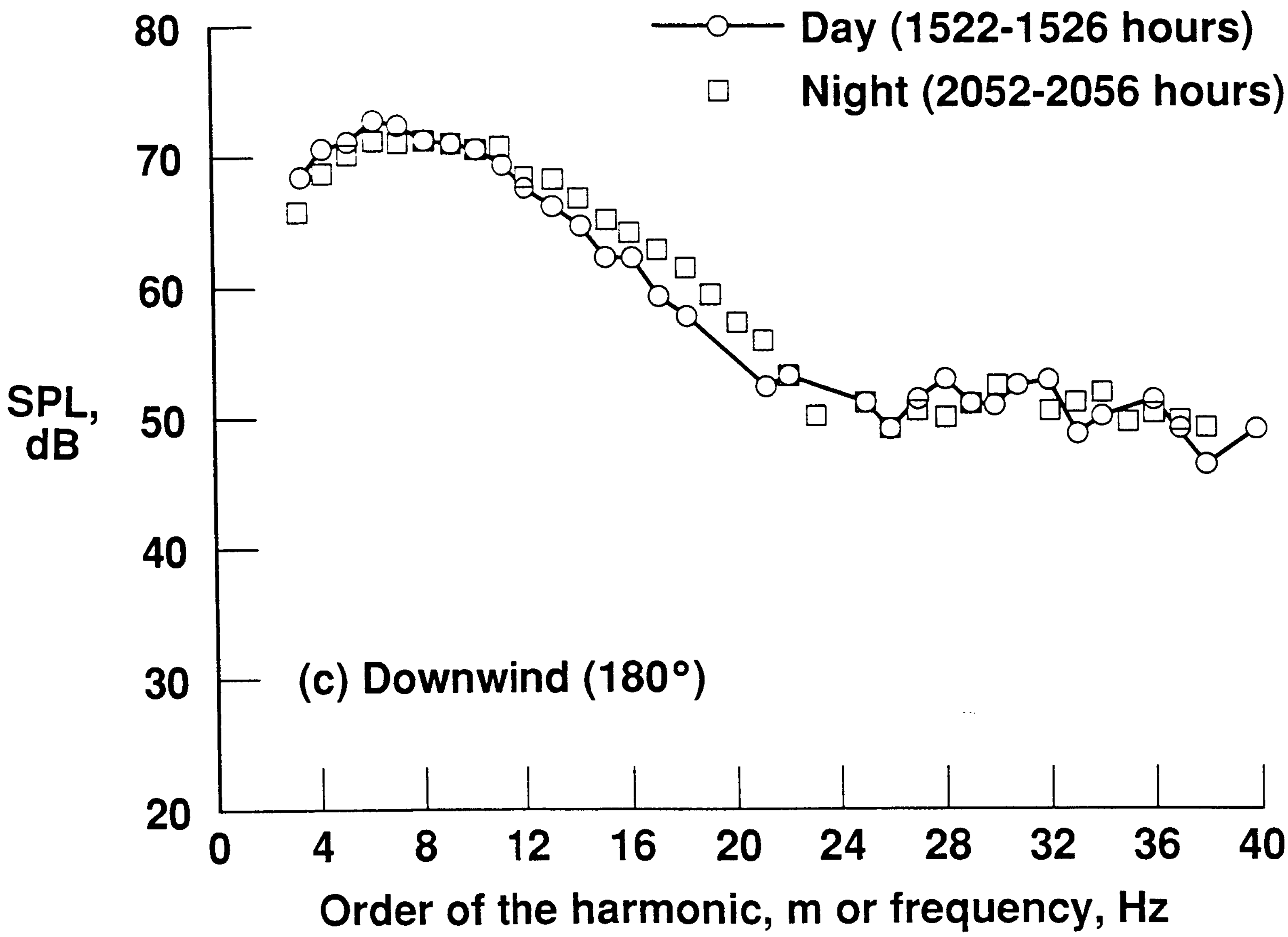


FIGURE 16. - (CONT.)

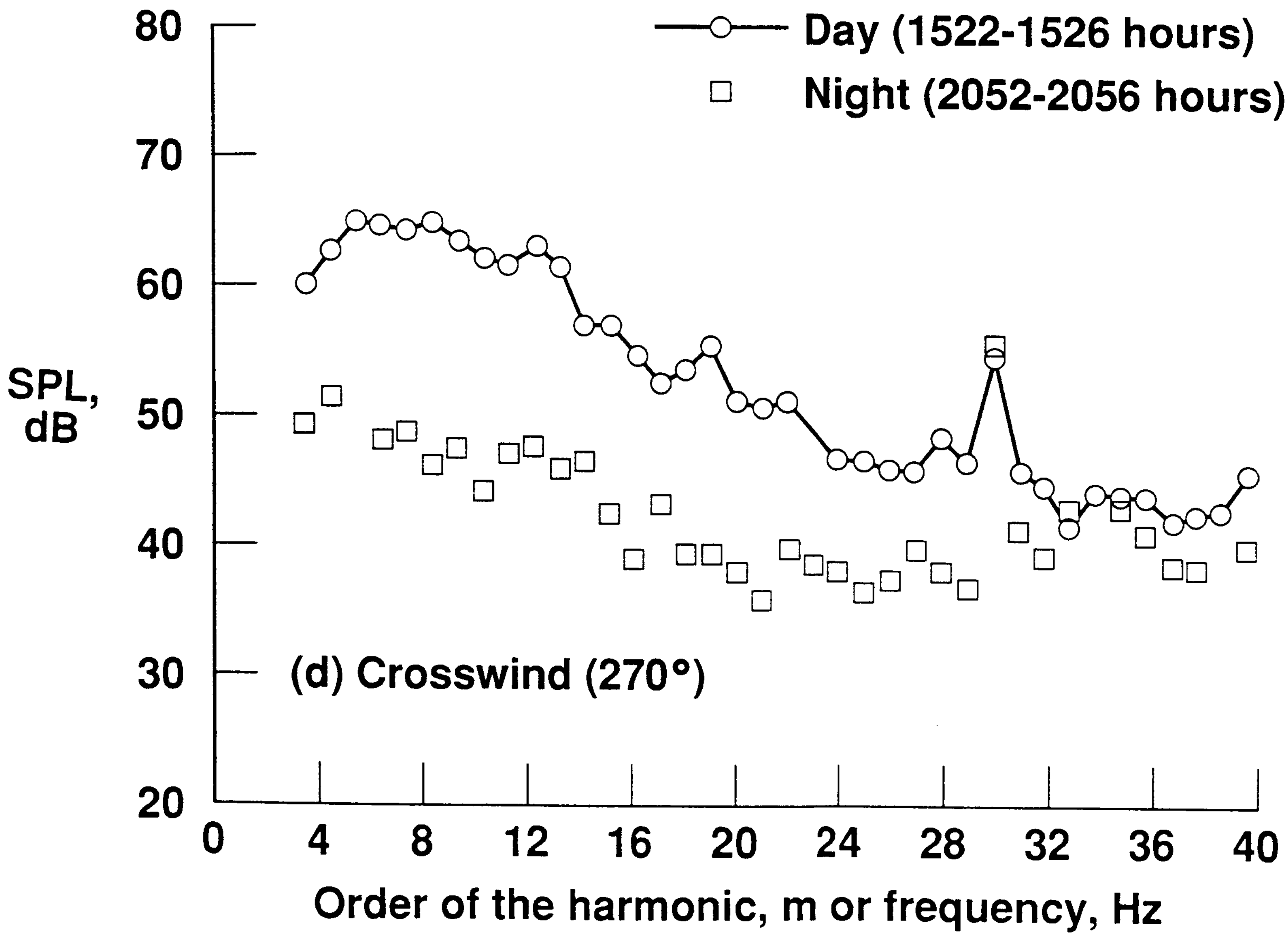


FIGURE 16. - (CONCL.)

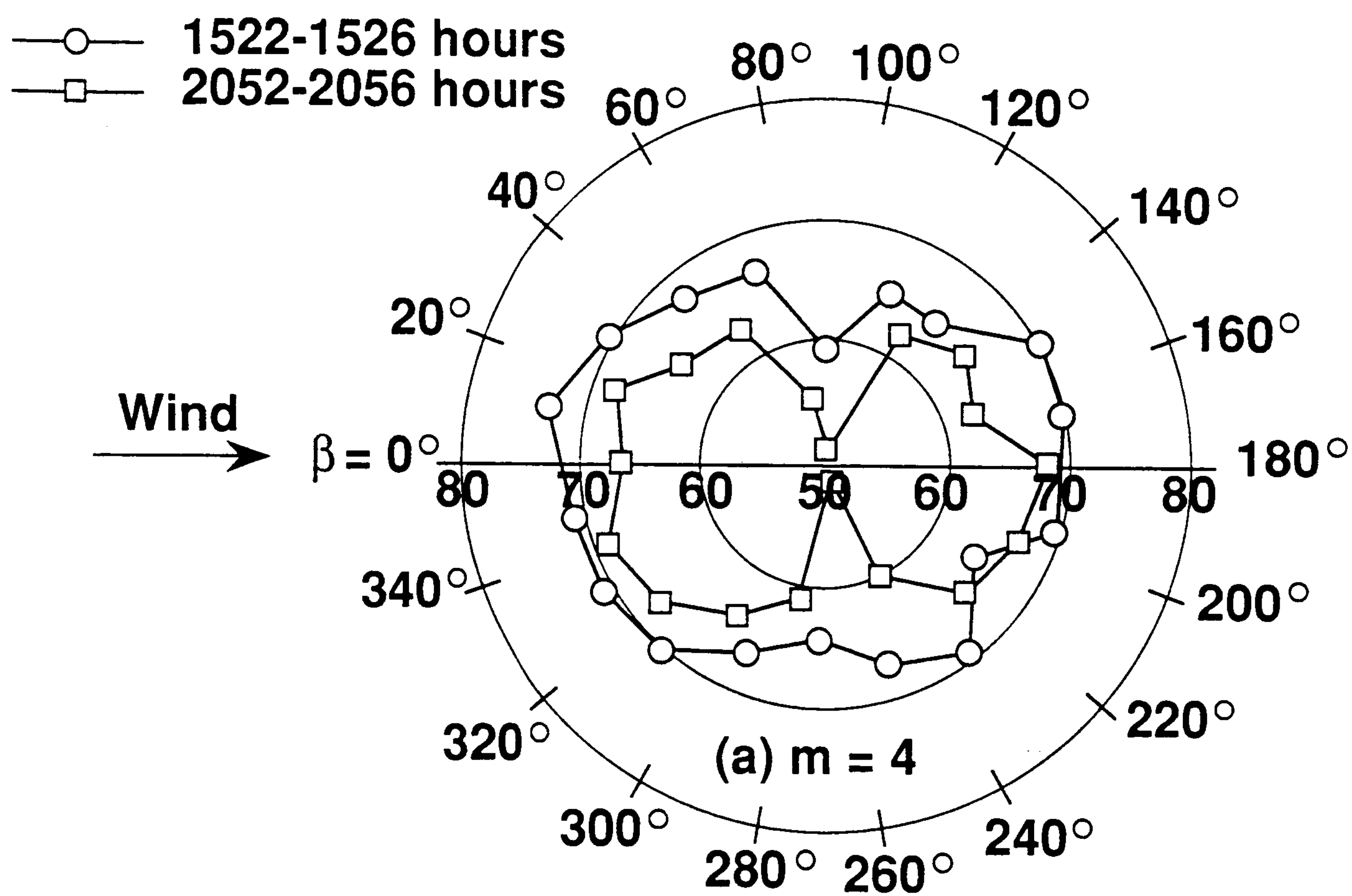


FIGURE 17. — Comparisons of the Narrow Band Polar Diagrams for Several Rotational Harmonics of the WTS-4 Wind Turbine Generator Operating Under Daytime and Nighttime Conditions. V=7.2-7.4 m/s, P=0.10-0.13 MW, d=200 m, RPM=30.

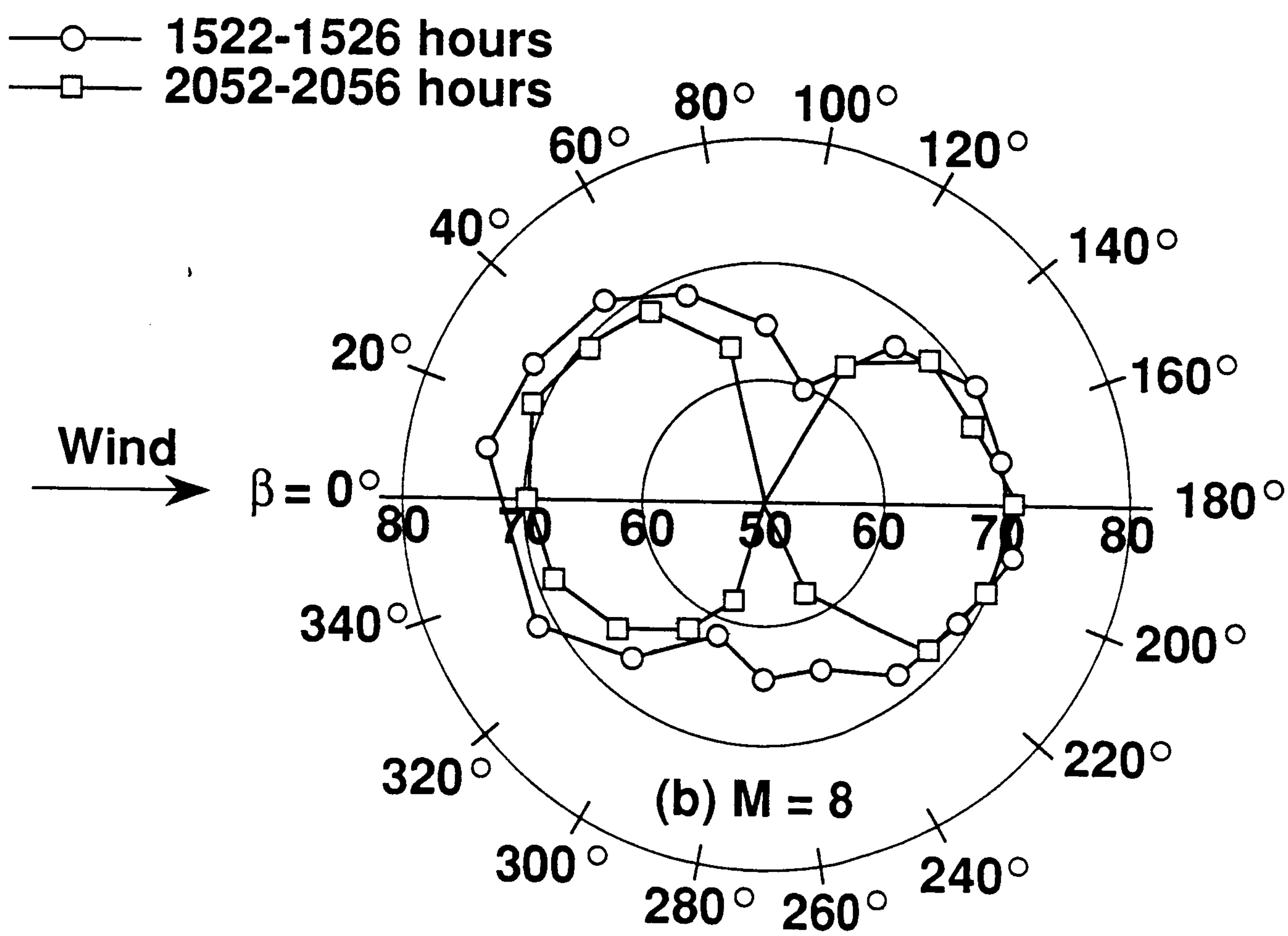


FIGURE 17.— (CONT.)

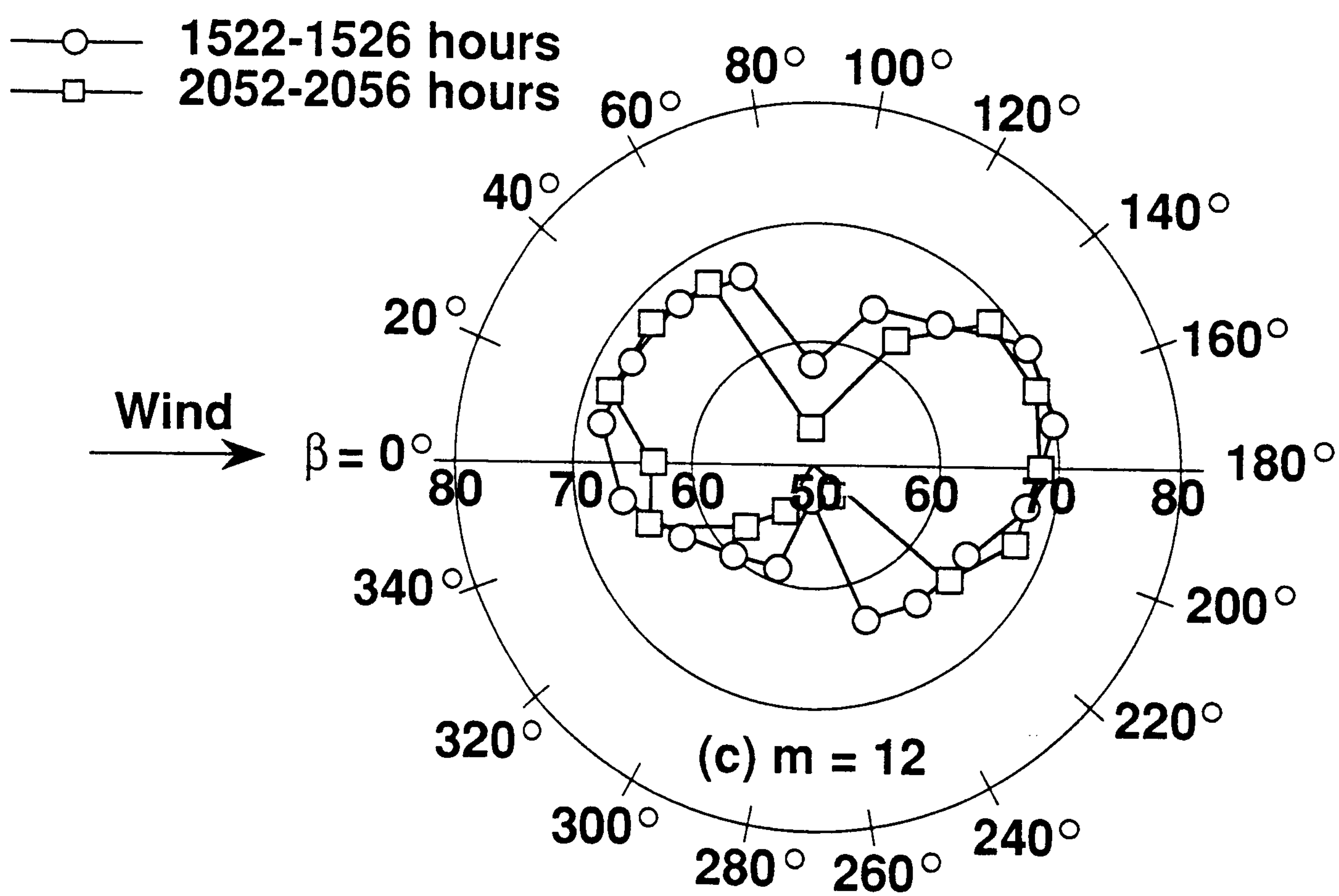


FIGURE 17.— (CONT.)

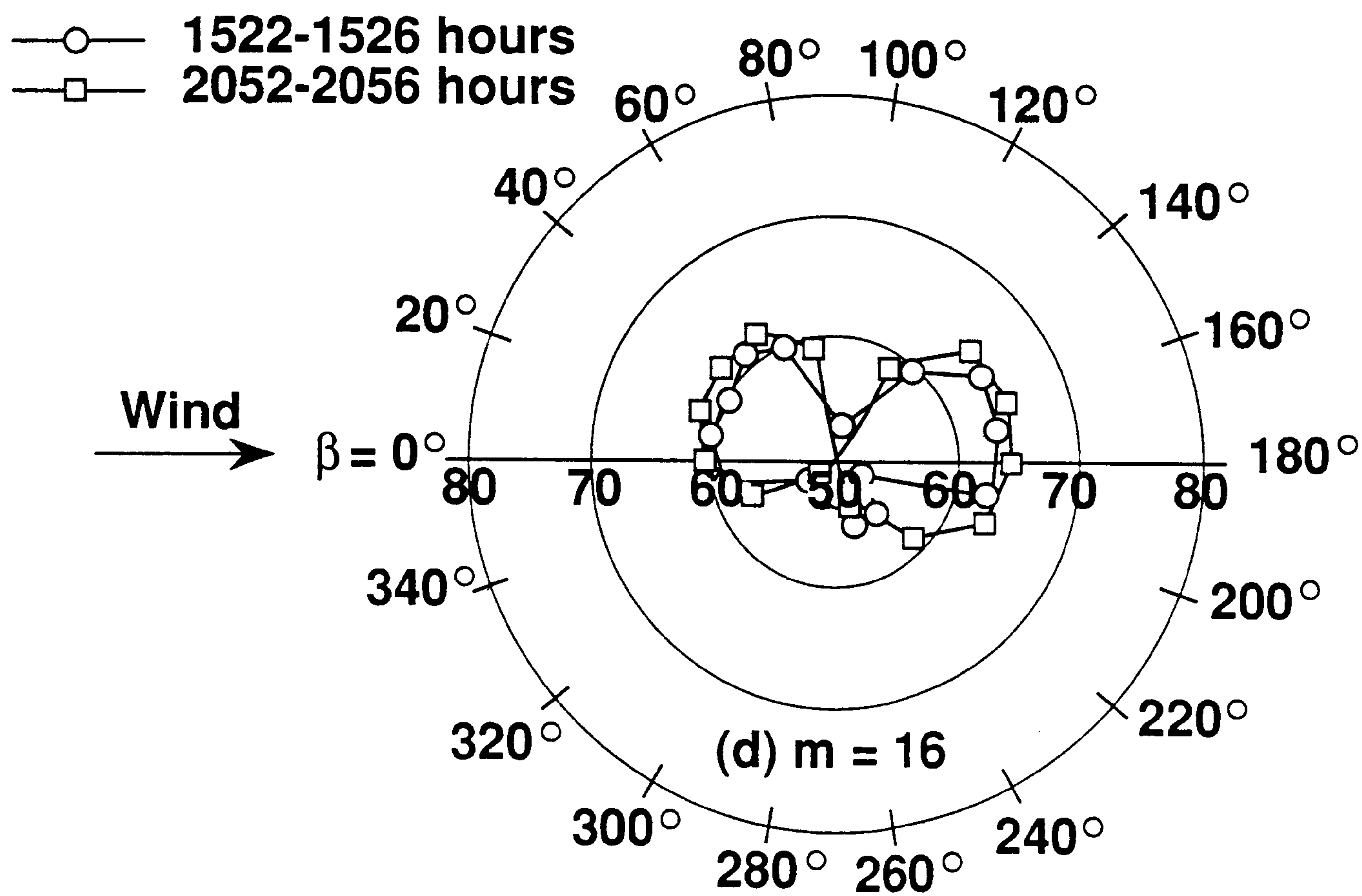


FIGURE 17.— (CONT.)

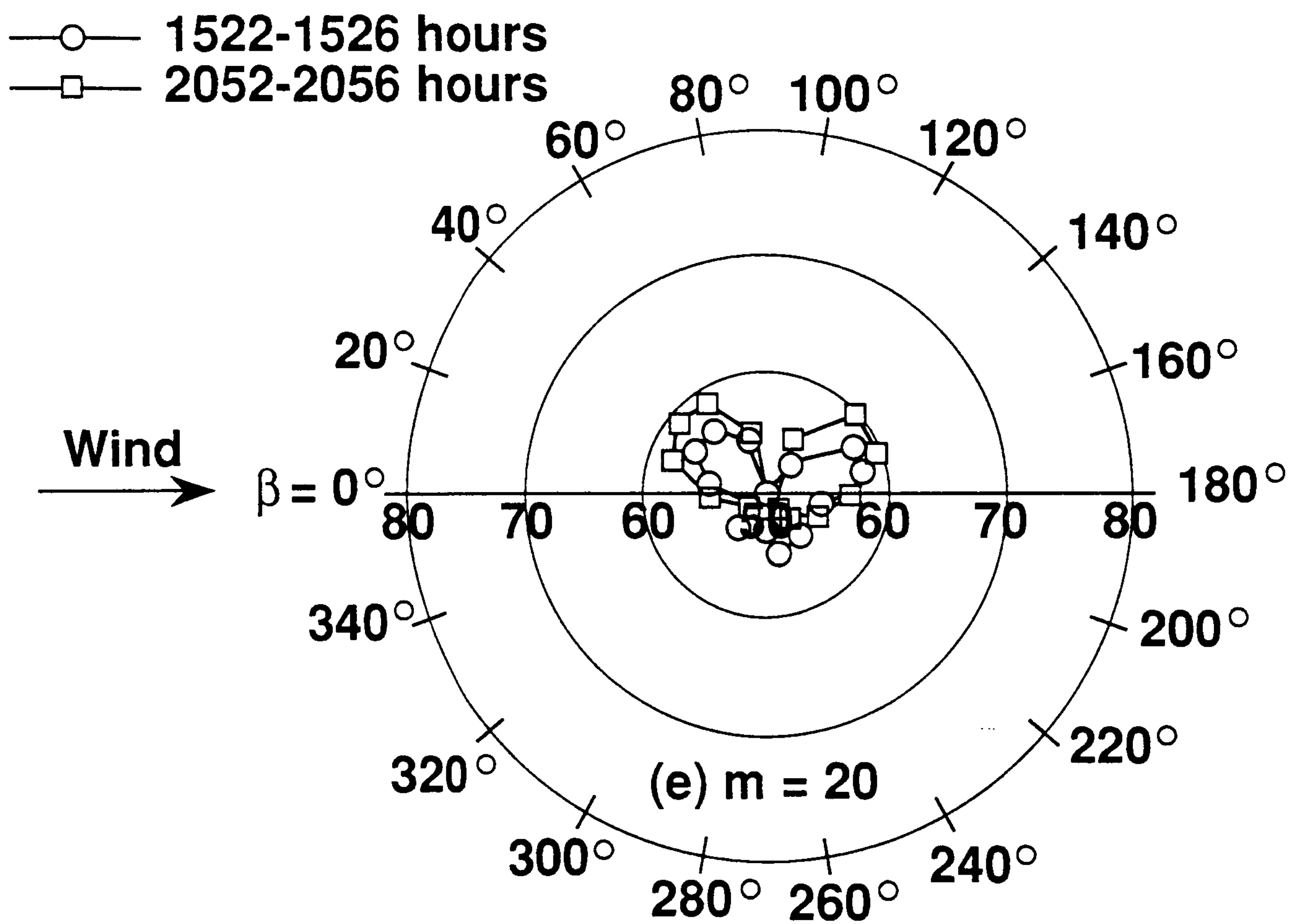


FIGURE 17.– (CONCL.)

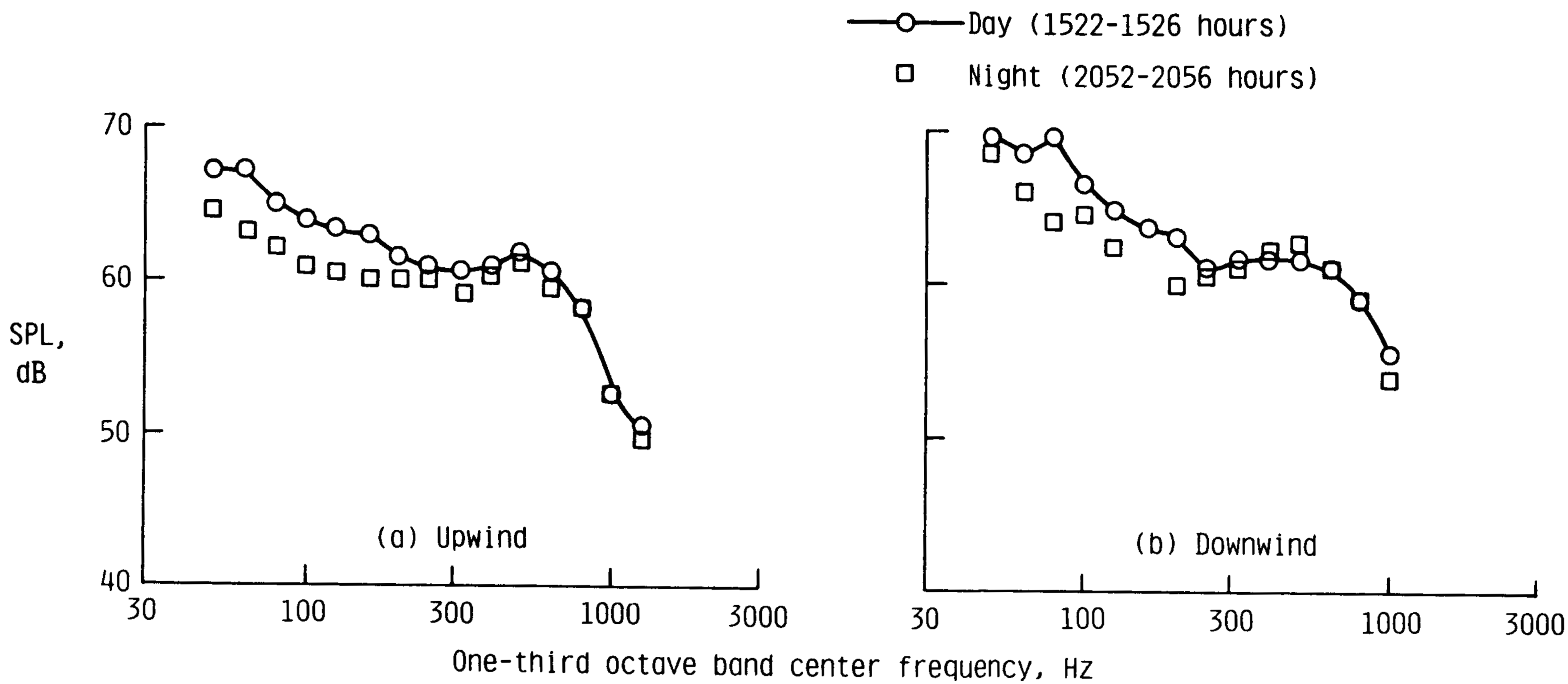


FIGURE 18.– Comparisons of the One-Third Octave Band Spectra for the WTS-4 Wind Turbine Generator During Daytime and Nighttime Operations. V=7.2-7.4 m/s, P=0.10-0.13 MW, d=200 m, RPM=30.

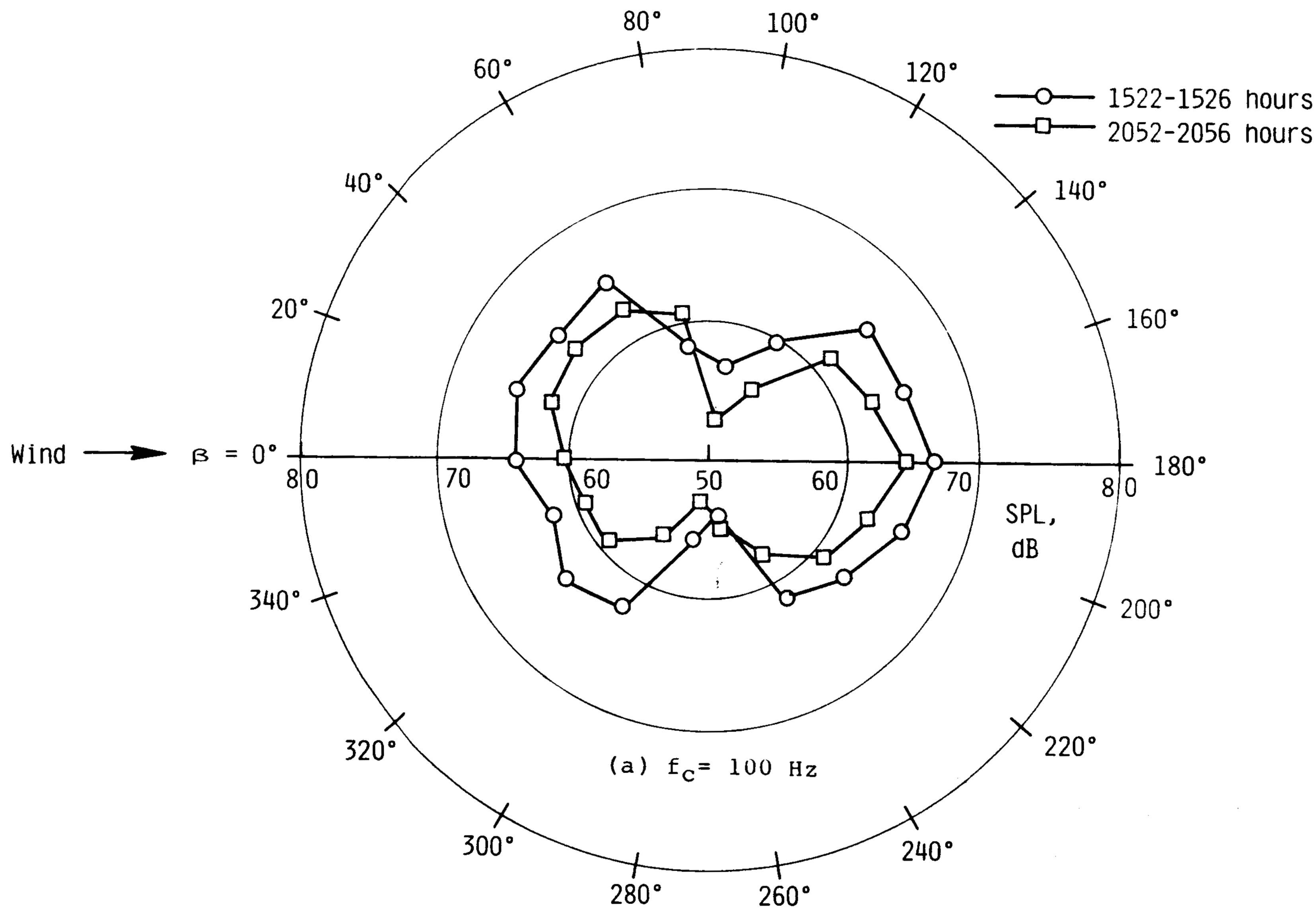
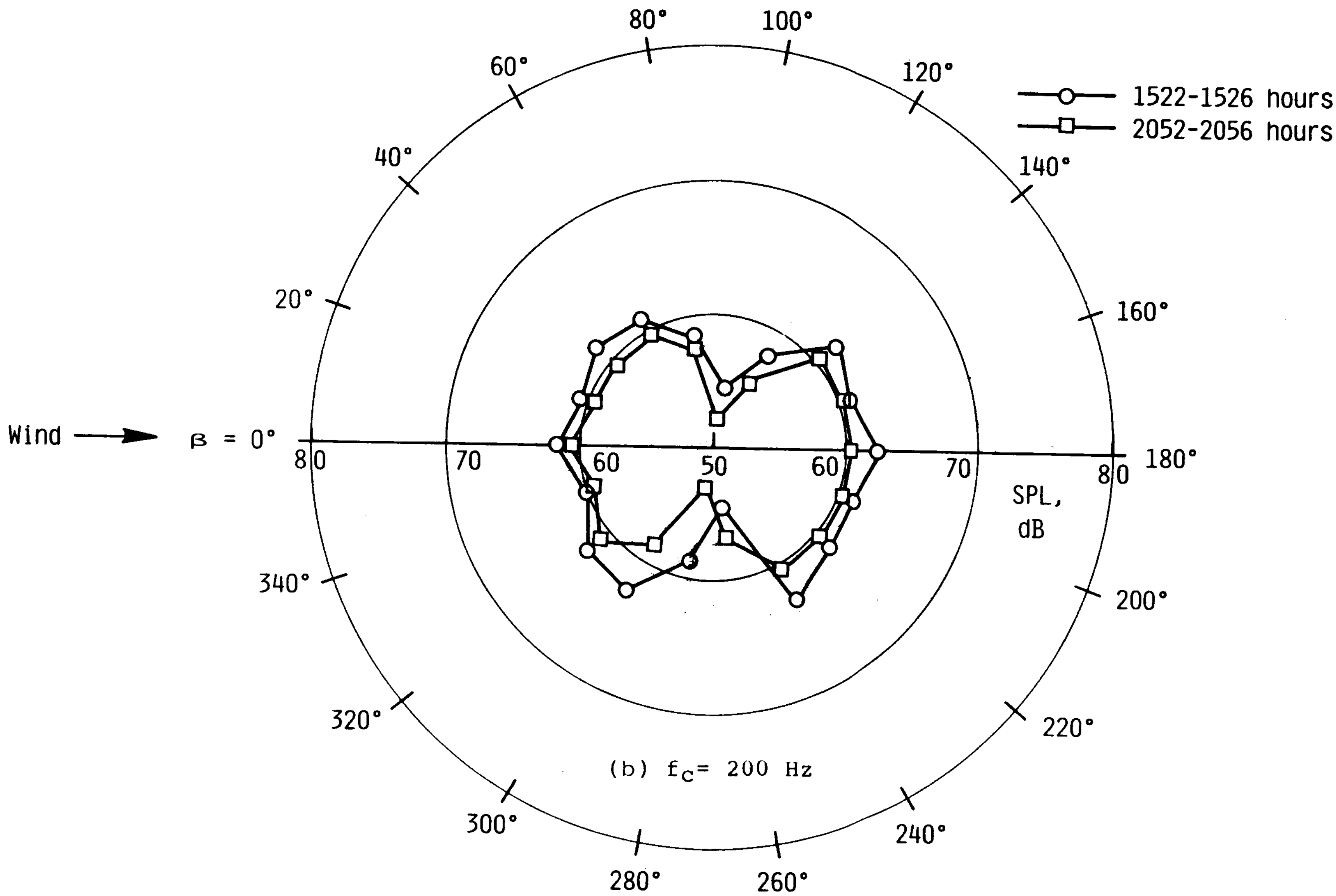
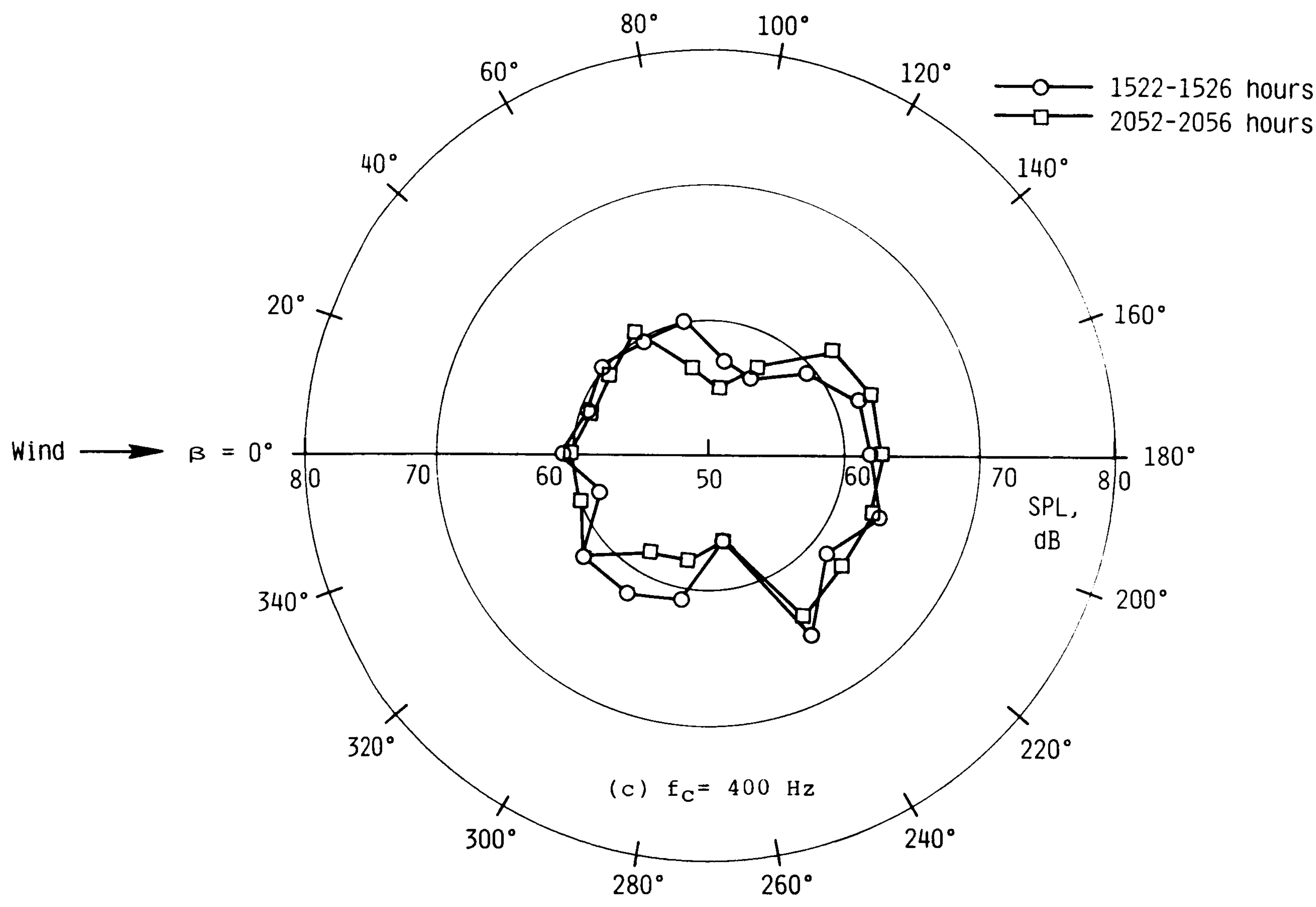


FIGURE 19.— Comparisons of the Broad Band Polar Diagrams for the WTS-4 Wind Turbine Generator Operating Under Daytime and Nighttime Conditions. V=7.2-7.4 m/s, P=0.10-0.13 MW, d=200 m, RPM=30.



(b) f_c = 200 Hz

FIGURE 19.— (CONT.)



(c) f_c= 400 Hz

FIGURE 19.— (CONT.)

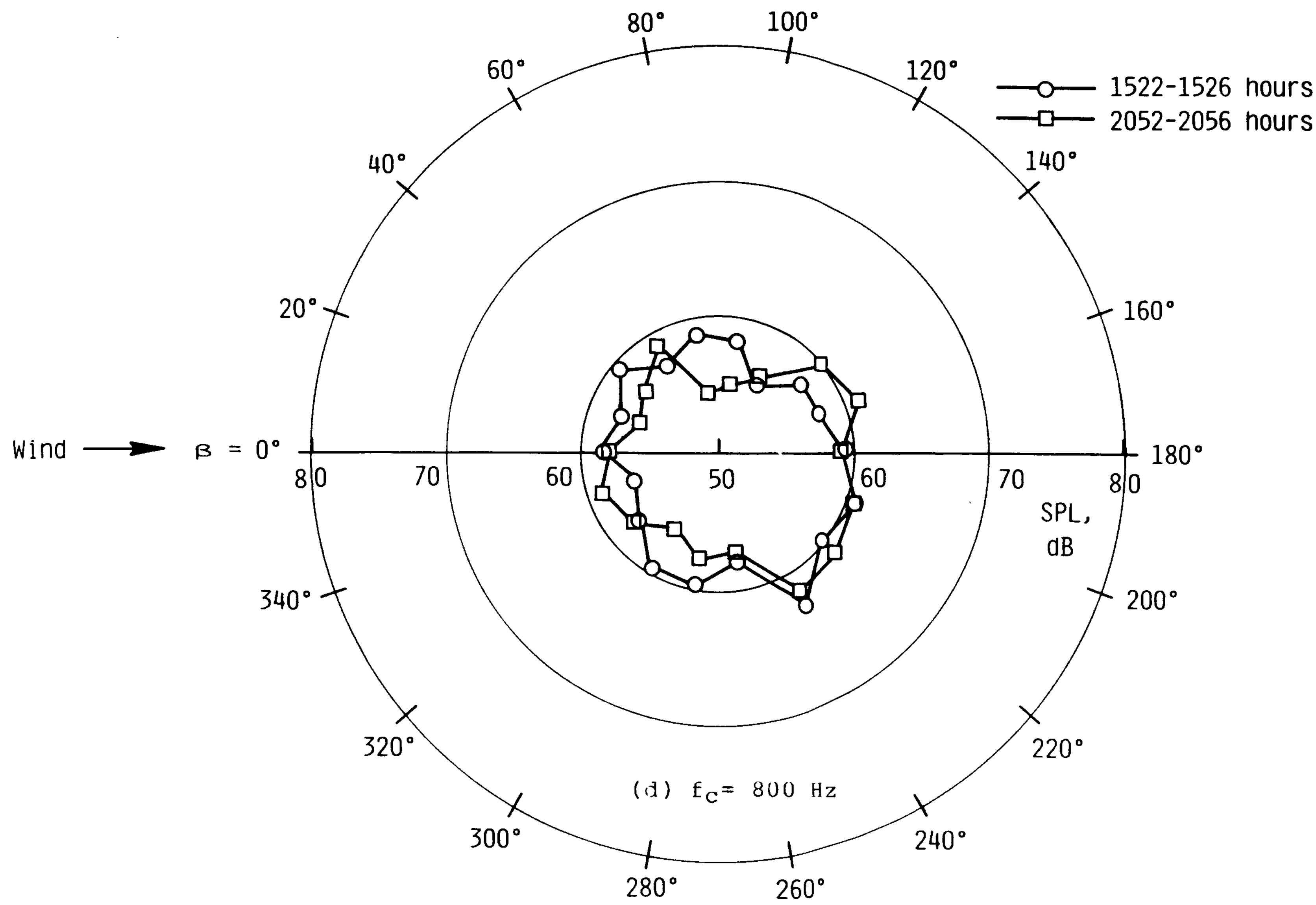


FIGURE 19.— (CONCL.)

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16. Abstract

Results are reported from a large number of Simultaneous Acoustic Measurements around a Large Horizontal Axis Downwind Configuration Wind Turbine Generator. In addition, comparisons are made between measurements and calculations of both the discrete frequency rotational harmonics and the broad band noise components. Sound Pressure Time Histories and Noise Radiation Patterns; as well as Narrow Band and Broadband Noise Spectra are presented for a range of operating conditions. The data are useful for purposes of environmental impact assessment.

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